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Université Toulouse 3 Paul Sabatier (UT3 Paul Sabatier)

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Loïc TUDESQUE
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ANALYSE TEMPORELLE ET SPATIALE DES COMPOSANTES CHIMIQUES, HYDROMORPHOLOGIQUES ET DIATOMIQUES EN RELATION AVEC LES CHANGEMENTS GLOBAUX

JURY
Prof. René Le Cohu (Université Paul Sabatier - Toulouse III)
Prof. Sergi Sabater (Université de Girone - Espagne)
Dr. Isabelle Lavoie (Institut National de la Recherche Scientifique - Québec)
Dr. Michel Coste (Cemagref - Bordeaux)
Dr. François Delmas (Cemagref - Bordeaux)

Ecole doctorale :
Sciences Ecologiques, Vétérinaires, Agronomiques et Bioingénieries (SEVAB)
Unité de recherche :
Laboratoire Evolution et Diversité Biologique (UMR 5174)
Directeur(s) de Thèse :
Prof. Sovan Lek
Dr. Michel Coste
Rapporteurs :
Prof. Sergi Sabater
Dr. Isabelle Lavoie

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ANALYSE TEMPORELLE ET SPATIALE

DES COMPOSANTES CHIMIQUES, HYDROMORPHOLOGIQUES ET DIATOMIQUES

EN RELATION AVEC LES CHANGEMENTS GLOBAUX

Co-direction :

PROF. SOVAN LEK

DR. MICHEL COSTE

Laboratoire Evolution & Diversité Biologique – UMR CNRS/UPS/ENFA 5174
Université Paul Sabatier, Toulouse III

"The planet has been pushed into a new geological area: the Anthrophocene"

(Paul Crutzen)

"Unsustainable development has pushed mankind into a new social area: the Anthropo'sin"

(l'auteur)

THANKS Remerciements

Cette étape est un passage obligé que je ne peux donc passer sous silence, que je me thèse serait mal venu. Alors, pour mes remercie'man, je vais faire so'mère comme pour les pages à venir : Mère si !

Vous avez compris qui je place en premier…et ce n'est pas une question de chronologie !

Un special « Thanks » à mes deux co-directeurs de Thèse : Sovan Lek pour m'avoir accordé sa confiance dès mon arrivée au laboratoire et pour m'avoir permi de réaliser ce travail et à Michel Coste à qui je dois ma carrière de diatomiste.

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AVANT-PROPOS

Ce manuscrit regroupe mes principaux travaux effectués au sein du Laboratoire Evolution et Diversité Biologique (EDB-UMR 5174) ces dernières années dans le cadre du projet européen Euro-Limpacs et du programme CNRS-Nouragues (Project Amazonie phase 2). Ces études ont donné lieu à un article publié et deux articles sous presse soumis dans des revues internationales à comité de lecture. Un quatrième article est en cours de préparation. Chaque article constitue un chapitre de thèse. Ces chapitres s'articulent autour d'une thématique scientifique commune qui est celle des « changements globaux » affectant les hydrosystèmes fluviaux. En arrière plan se positionne le contexte législatif de la Directive Cadre Européenne sur l'eau (DCE), catalyseur de la recherche scientifique européenne en hydrobiologie depuis une décennie.

Différents aspects relatifs aux changements globaux ont été abordés :

- La physico-chimie et les séries temporelles (respectivement chapitres 1 et 3, chapitre 1)
- L'hydromorphologie (chapitre 2)
- La variation des échelles spatiales de l'occupation des sols (chapitres 2 et 3)
- La bio-indication centrée sur les diatomées benthiques (chapitres 3 et 4)

Les aires d'études concernées sont celles du bassin hydrographique Adour-Garonne et de cours d'eau de la réserve naturelle des Nouragues en Guyane Française.

L'introduction générale replace chacun des chapitres dans la thématique qu'il aborde.

La conclusion générale constitue une synthèse des principaux résultats avec comme ambition d'apporter des éléments pertinents en réponse aux attentes de la Directive Cadre Européenne sur l'Eau.

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Chapitre 2 - Links between stream reach hydromorphology and land cover at different spatial scales in the Adour-Garonne Basin (SW France)

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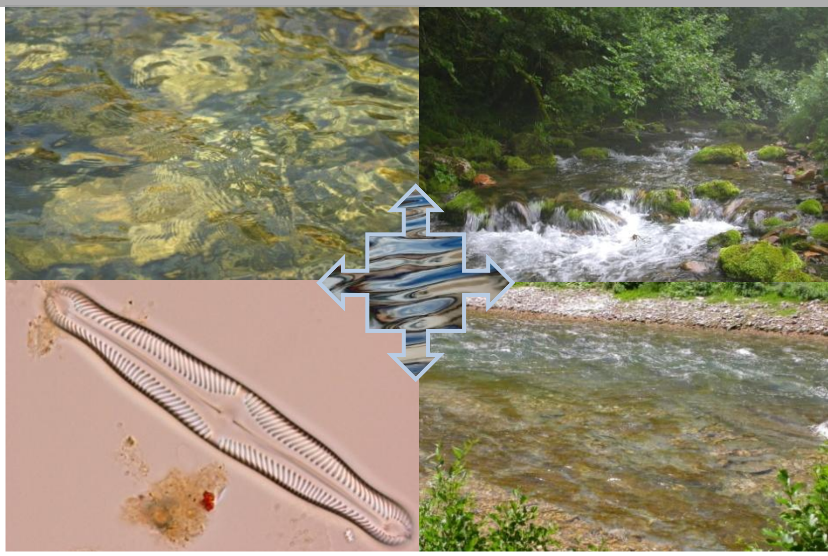
Chapitre 4 - Influence of small-scale gold-mining on French Guiana streams: Are diatom assemblages valid disturbance sensors?

CONCLUSIONS GÉNÉRALES ET PERSPECTIVES

ANNEXES

INTRODUCTION GÉNÉRALE



Les transformations profondes, rapides, voire brutales des conditions environnementales planétaires sont de plus en plus flagrantes. Les observations portées sur les événements passés et présents ont conduit à la conclusion que la planète s'est déportée hors de son champ de variabilité naturelle établi depuis au moins un demi-million d'années (Steffen *et al*., 2004) ; alors que dans le passé les principales causes des modifications environnementales tenaient leurs origines dans les grandes forces naturelles (volcanisme, tectonique des plaques) ou extraterrestres (radiations solaires, impacts météoritiques, changement de l'orbite terrestre, modification de l'inclinaison de l'axe de la terre). Aujourd'hui, l'évolution d'*Homo sapiens sapiens*, accompagnée de l'accroissement incontrôlé de sa population et du développement sans frein des sociétés (demande croissante pour l'énergie, la nourriture, les biens, les services, l'information, l'accumulation des déchets) constitue la source principale du phénomène « changement global ».

1. Le changement global

Le terme de « changement global » est souvent sujet à restriction ou à confusion avec le terme de « changement climatique ». Ce dernier touche les consciences avec plus de force et d'empathie et ses effets se perçoivent avec une visibilité directe. Le changement climatique et les effets qui lui sont associés, souvent de nature catastrophique, sont visibles, spectaculaires et médiatisées. Le changement global, incluant la composante climatique, affecte la planète dans toutes ses composantes terrestres (couverture et utilisation des sols, cycles biogéochimiques), aquatiques (circulation océanique, cycle du carbone, cycle de l'eau), biologiques (perte de diversité, réseaux trophiques), aériennes (circulation atmosphérique, climat) et humaines (population, économie, utilisation des ressources, transport, communication, pollution, santé). Toutes ces composantes interdépendantes sont imbriquées et liées par le biais de relations complexes. Les modifications qui les affectent ont des conséquences parfois visibles, mais pour la plupart celles-ci restent insidieuses, difficiles à identifier, à évaluer et à anticiper. Les connaissances sont relativement limitées quant à la compréhension du fonctionnement de la Terre comme système global. Comment se connecte chaque composante les unes aux autres et quelle est leur importance respective sont des interrogations récurrentes. Ainsi malgré l'évidence du phénomène, celui-ci reste relativement opaque.

Depuis une vingtaine d'années, la compréhension du changement global et du fonctionnement des processus planétaires focalisent un énorme effort de recherche. La communauté scientifique aussi bien que les organisations internationales gouvernementales et non gouvernementales considèrent que le niveau actuel de consommation, particulièrement dans les pays développés, ne pourra pas être durable car il y a un réel danger de plonger la planète dans un nouvel état; et c'est sur ce que sera ce nouvel état que le débat se focalise. En l'an 2000, le prix Nobel de Chimie, Paul Crutzen, déclara que l'échelle du changement était si grande, qu'en seulement 250 ans, la société humaine a poussé la planète dans une nouvelle ère géologique : l'Anthropocène.

1.1. Les hydrosystèmes et le changement global

Les systèmes aquatiques continentaux font partie intégrante des milieux affectés par le changement global à la fois de manière directe et visible (exploitation de la ressource, obstruction à l'écoulement) et indirect (changement climatique). Les rivières sont menacées par les activités socio-économiques qui dégradent les conditions environnementales en altérant les sols et le climat qui, à leur tour, affectent la quantité (hydrologie) et la qualité de l'eau (chimie, biologie). Depuis les années cinquante où les changements globaux se sont accélérés, l'utilisation de la ressource en eau douce ainsi que son contrôle par le biais de barrages ou de canalisations se sont fortement amplifiés (Oki & Kanae, 2006). Approximativement 40% de la surface du globe est occupée par les cultures et les prairies. L'utilisation des engrais riches en Phosphore et en Azote a augmenté respectivement de deux et sept fois alors que les cultures irriguées ont augmenté de 100% en quarante ans (Tilman *et al.*, 2001). Les pressions globales sur la ressource en eau sont en constante augmentation pour la production hydroélectrique et le contrôle des débits (Stevenson & Sabater, 2010). De telles perturbations ont, et continuent, d'altérer les régimes hydrologiques, la diversité et la disponibilité des habitats, l'apport en nutriments, sédiments et toxiques dans les rivières (Sabater, 2008). La combinaison des ces perturbations a des effets encore mal connus sur le fonctionnement des écosystèmes aquatiques susceptible d'impacter des dizaines de milliers d'espèces.

Les ruisseaux, les rivières et les fleuves constituent des écosystèmes originaux du fait de leur fonctionnement linéaire associé à une emprise spatiale relativement restreinte au regard des surfaces drainées. Ces particularités physiques font des hydrosystèmes des milieux récepteurs d'une extrême sensibilité, tout particulièrement vis-à-vis des modifications touchant l'occupation des sols. Les caractéristiques d'occupation des sols (ou du paysage) ont un impact sur les divers compartiments des écosystèmes fluviaux, qu'il s'agisse des caractéristiques physiques, hydrologiques, chimiques ou biotiques.

1.2. Influence du paysage et des caractéristiques d'occupation des sols

Pendant longtemps, l'occupation des sols a généralement été considérée comme un sujet environnemental de dimension locale. De nos jours il apparait de façon de plus en plus évidente que sa prise en considération doit être abordée de façon globale. Les modifications d'utilisation des sols, que ce soit par conversion des espaces naturels ou par changement des pratiques agricoles, ont refaçonné une très grande partie des paysages de la planète. Bien que l'occupation et l'utilisation des sols soient extrêmement variables à travers le monde, les conséquences ultimes sont invariablement les mêmes : l'acquisition des ressources naturelles pour le besoin immédiat des sociétés accompagnée de l'accroissement des dégradations des conditions environnementales (la déforestation, le lessivage des sols, la fragmentation des cours d'eau, l'hyper-eutrophisation en sont quelques exemples).

Plusieurs décennies de recherche scientifique ont démontré l'impact du changement d'occupation des sols sur les modifications des cycles biogéochimiques (induisant un changement de la composition chimique de l'atmosphère) et des processus biogéophysiques (absorption et disposition de l'énergie à la surface de la terre ; Feddema *et al.*, 2005) jusqu'aux modifications profondes du fonctionnement des écosystèmes (Folay *et al.*, 2005). Historiquement, il est reconnu que les transformations d'occupation des sols ont induit une modification des températures à l'échelle du globe. Les simulations mettent en évidence les variations des températures diurnes en réponse aux modifications d'occupation des sols. Pour le futur, les scénarios font état d'une hausse potentielle de température de l'ordre de 1 à 2 degrés particulièrement dans les zones déforestées. D'autre part, il a été démontré qu'actuellement, parmi les cinq plus importants facteurs responsables des changements de la biodiversité à l'échelle mondiale, les changements d'occupation des sols arrivent au premier rang (suivi par la concentration en CO_2 atmosphérique, les pluies acides et la déposition d'Azote, le climat et les échanges biotiques - introduction d'espèce dans les écosystèmes). Concernant plus spécifiquement les écosystèmes aquatiques, ceux-ci sont impactés à parts égales par les changements d'occupation des sols et par les interactions biotiques (Sala *et al.*, 2000).

L'Homme a également transformé les cycles hydrologiques des eaux douces de façon à pourvoir à ses besoins : à savoir sa consommation domestique, sa production industrielle et l'irrigation des cultures. Les relations étroites établies entre l'occupation des sols et la qualité des eaux ont largement été démontrées à travers de nombreuses études au cours de ces deux dernières décennies. Il y a de nombreuses évidences qui montrent que dans les bassins hydrographiques dominés par l'agriculture et l'urbanisation, les lacs et les rivières ont un niveau d'eutrophisation significativement plus élevé (Pereira *et al.*, 2010). La hausse des apports en éléments nutritifs dans les eaux est principalement associée à l'utilisation massive et excessive de fertilisants, à l'importance des densités des élevages, à la diminution de la couverture forestière, à l'accroissement des zones urbaines ainsi qu'à la réduction des zones humides (Houlahan & Findlay, 2004). Les apports dans la biosphère en éléments nutritifs d'origine anthropique provenant des engrais ou des polluants atmosphériques ont maintenant dépassé les sources naturelles et ont des effets étendus sur la qualité des eaux des écosystèmes à la fois marins et d'eau douce (Matson *et al.*, 1997 ; Bennett *et al.*, 2001). En plus de son influence directe sur la qualité des eaux, l'utilisation des sols interagit avec d'autres facteurs qui affectent l'état des hydrosystèmes, incluant le changement climatique, l'apparition et le développement des espèces invasives ou bien encore la fragmentation.

Dans de nombreux pays, le contrôle de l'occupation des sols se fait à proximité des rivières, des lacs ou des zones humides par le biais du maintien de zones tampons. De manière implicite, cette méthode de préservation des milieux repose sur la conviction que ces zones adjacentes ont un effet sur la qualité de l'eau. Les décideurs, les autorités de gestion des milieux aquatiques doivent donc déterminer quelle est l'extension spatiale adéquate de ces zones tampons afin que leur action de protection des milieux soit efficace. Les recherches qui ont examiné les relations entre l'occupation des sols et la qualité des eaux se sont pour la plupart focalisées sur les relations établies à l'échelle du bassin versant ou bien à l'échelle locale.

1.3. Importance des échelles spatiales dans les connexions des processus écologiques

D'une façon générale, les hydrosystèmes sont caractérisés par les particularités de leur biotope et de leur biocénose observées à l'échelle de la station (emprise spatiale de quelques mètres à une centaine de mètres). La compréhension du fonctionnement des écosystèmes passe alors nécessairement par l'identification des mécanismes sous-jacents qui déterminent ces patrons observés localement (Levin, 1992). Pour ce faire, les connaissances actuelles ont intégré de manière croissante la notion de facteurs de contrôle spatialement imbriqués (Allan, 2004). Les métriques environnementales à large échelle telles que le climat, la géologie ou la topographie influencent les processus géomorphologiques façonnant les cours d'eau à échelle intermédiaire, et qui eux même détermineront les conditions d'habitat et la qualité biogène observées aux plus petites échelles. La reconnaissance des rivières en temps que mosaïque complexe d'habitats et de gradients environnementaux (à haut degré de connectivité et de complexité spatiale) passe par la prise en compte d'un vaste panel d'échelles spatiales. Ainsi, de très nombreuses études se sont tournées vers la compréhension de l'organisation hiérarchique des hydrosystèmes depuis les échelles les plus larges, comprenant la totalité des bassins versants, jusqu'aux échelles locales les plus fines telles que les micro-habitats, en passant pas des échelles intermédiaires telles que le sous-bassin hydrographique, le segment ou le faciès d'écoulement.

Les caractéristiques physiques, chimiques et biotiques des milieux aquatiques sont donc structurées par des facteurs de contrôle agissant à différentes échelles spatialement imbriquées. Identifier ces facteurs et définir leur influence sur les milieux devient un enjeu majeur de l'écologie. De nombreuses études témoignent que les facteurs du paysage influencent les écosystèmes lotiques à travers un large panel d'échelles spatiales. Néanmoins, l'influence de ces facteurs à différentes échelles spatiales reste difficile à séparer. Par ailleurs, très peu d'études ont comparé l'influence de ces facteurs sur les écosystèmes aquatiques en fonction de leur emprise spatiale, que ce soit à l'échelle du bassin versant *ou à l'*échelle locale. Ainsi, il est attendu que la force des relations reliant les caractéristiques d'occupation des sols avec les différentes variables abiotiques ou biotiques soit variable selon l'emprise spatiale considérée. L'enjeu étant alors de déterminer l'intensité des liens qui se tissent entre des métriques mesurées localement et les différents patrons d'occupation des sols.

Parmi les facteurs de contrôle agissant sur les milieux aquatiques, l'hydromorphologie tient un rôle structurant central. Tout particulièrement, c'est elle qui définie les caractéristiques physiques de l'habitat auxquelles sont soumises les communautés végétales et animales. Les caractéristiques hydromorphologiques constituent un cadre physique à travers lequel les interactions biotiques et abiotiques se structurent. Aussi, la moindre modification ou altération de ces conditions induit un effet direct ou indirect sur l'hydrologie, qui de fait, devient un facteur de stress.

Les unités hydrographiques et l'emboitement des échelles correspondent à une organisation spatiale hiérarchique en poupées russes dans laquelle un système d'ordre élevé comprend des sous-systèmes qui comprennent eux-mêmes d'autres sous-systèmes et ainsi de suite. Parallèlement à cette organisation géographique, se superpose et s'imbrique une organisation fonctionnelle elle aussi hiérarchisée depuis les processus géochimiques jusqu'à la structuration des réseaux trophiques. Stevenson (1997) propose un modèle complexe d'interrelations hiérarchiques depuis des métriques à très large échelle, de type climatique ou géologique, jusqu'aux échelles les plus fines correspondant aux réponses biologiques. Au sein de cette organisation, les relations qui sont établies peuvent être de nature directe ou bien se mettre en place de façon indirecte par le biais de multiples connexions (Allan, 2004). Dans le contexte de prise en considération des caractéristiques d'occupation des sols, la figure 1 reprise de Allan (1997) illustre les liens possibles par lesquels les métriques du paysage peuvent impacter les métriques biotiques. Quantifier la corrélation entre ces deux types de métriques peut également être envisagé. Un impact sur la biocénose peut être dû à des causes multiples, ou bien à une cause dominante.

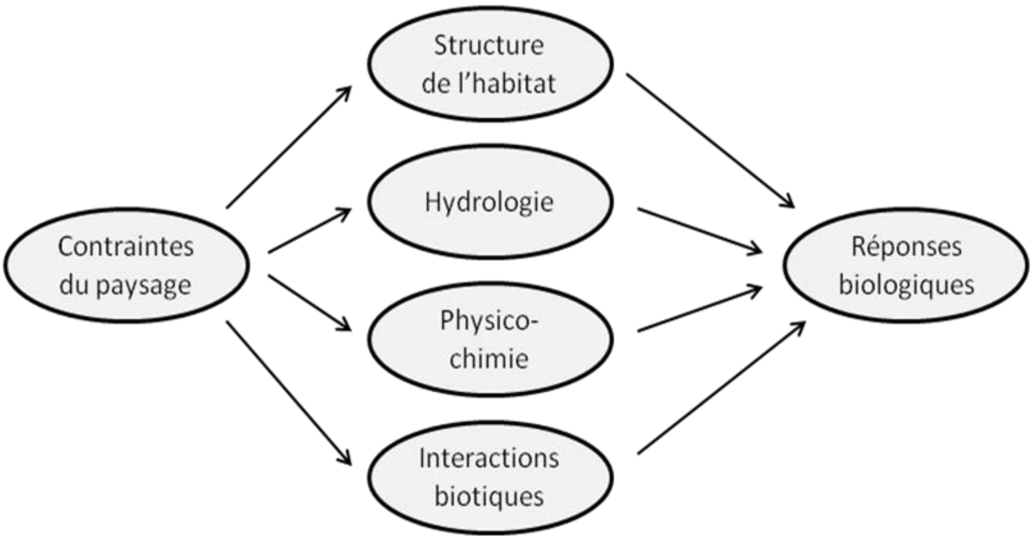


Figure 1*. Différentes connexions pouvant expliquer une relation significative entre les métriques du paysage et les métriques de réponses biologiques (adaptée de Allan, 2004).*

Tout état d'une masse d'eau s'inscrit dans une dynamique de systèmes écologiques emboités, une dynamique dont il faut tenir compte pour orienter un système donné vers une configuration désirable ou à l'inverse, pour l'écarter d'une configuration indésirable (Roche *et al.*, 2005). Une meilleure compréhension des écosystèmes et l'identification pertinente de l'emprise spatiale du paysage ayant le plus d'influence sur la qualité de l'eau à un point donné est une phase critique et essentielle pour la gestion efficace et pertinente de la ressource (Gove *et al.*, 2001). La considération de l'échelle appropriée doit alors être nécessairement inclue dans les outils décisionnels de gestion.

2. Implication de la recherche scientifique dans le cadre des lois et des mesures de protection environnementale

L'objectif des lois sur l'eau et des mesures de protection environnementale consiste à préserver la santé des milieux aquatiques en prévenant les détériorations, en apportant une protection à long-terme et en améliorant l'état des ressources (Bennion & Battarbee, 2007). Cet objectif ne peut être atteint que par le maintien des processus écologiques naturels et fonctionnels des écosystèmes.

L'Union Européenne (E.U.) a établi un cadre communautaire pour la protection et la gestion de l'eau : la Directive-Cadre Européenne sur l'Eau (DCE, European Parliament and Council, 2000). Dans un premier temps, les États membres doivent identifier et analyser les eaux européennes recensées par bassin et par district hydrographique. Ils adoptent ensuite des plans de gestion et des programmes de mesures adaptés à chaque masse d'eau. La directive-cadre poursuit plusieurs objectifs tels que la prévention et la réduction de la pollution, la promotion d'une utilisation durable de l'eau, la protection de l'environnement, l'amélioration de l'état des écosystèmes aquatiques et l'atténuation des effets des inondations et des sécheresses. Son objectif ultime est d'atteindre un «bon état» écologique et chimique de toutes les eaux communautaires d'ici à 2015. Cet objectif ambitieux implique la mise en œuvre de la recherche scientifique à la fois d'un point de vue fondamental et appliqué afin de cerner et d'anticiper les changements potentiels susceptibles d'impacter les écosystèmes aquatiques et, par la suite, de proposer des mesures appropriées de conservation des milieux.

Depuis 1984, l'Union Européenne mène une politique de recherche et de développement technologique basée sur des programmes-cadres pluriannuels (Programme-Cadre pour la Recherche et le Développement Technologique, PCRDT). Les PCRDT constituent le cadre général des activités de l'U.E. dans le domaine de la science, de la recherche et de l'innovation. Instrument utile favorisant la création d'un véritable espace européen de la recherche, les PCRDT exercent un impact important sur les activités de recherche dans les États membres. La thématique 6 est dédiée depuis le 6^{e} PCRD aux effets des changements globaux. C'est dans ce contexte et avec comme exigence la réponse aux attentes de la Directive Cadre Européenne qu'a été mis en place le projet Européen Euro-Limpacs – *Integrated Project to evaluate the Impacts of Global Change on European Freshwater Ecosystems* (n° GOEC-CT-2003-505540 du 6ème PCRDT). Ce projet était destiné à évaluer l'impact du changement global sur les écosystèmes d'eau douce européens.

Cas particulier de la Guyane française

La mise en œuvre de la DCE a entrainé une charge importante de travail de la part des États membres afin qu'ils puissent mener à bien leurs obligations. Celles-ci requièrent entre autres la surveillance d'un large panel de paramètres biotiques pour lesquels les États membres doivent adapter ou développer des méthodes de bio-indication. Concernant l'utilisation des diatomées comme indicateur biologique, la plupart des Etats membres de l'U.E. a choisi d'utiliser les méthodes indicielles déjà existantes pour l'évaluation du « statut écologique » des eaux (Kelly *et al.*, 2009). En France métropolitaine, c'est le cas de l'Indice Biologique Diatomées (IBD) récemment amélioré afin de mieux répondre aux recommandations de la DCE (Coste *et al.*, 2009).

Dans le contexte français, la DCE doit s'appliquer de la même façon à l'ensemble des départements métropolitains et d'outre-mer. Cependant, pour ces derniers, les spécificités tant du point de vue des caractéristiques naturelles des milieux aquatiques que de la nature et de la répartition des pressions anthropiques qu'ils subissent nécessitent une démarche particulière (Wasson, 2008). Spécialement en Guyane française, l'estimation de la qualité de l'eau par les diatomées est difficilement applicable par les méthodes indicielles existantes et notamment par l'IBD. La raison principale en est la méconnaissance de la microflore diatomique qui, à ce jour, n'a donné lieu à aucune publication, spécialement dans le domaine de la taxonomie. A cette difficulté d'identification des espèces s'ajoute la spatialisation fortement marquée de la nature des pressions anthropiques. Les zones côtières qui rassemblent la quasi-totalité des zones urbaines, sont sujettes aux rejets des eaux usées induisant une contamination chimique affectant la charge organique et/ou nutritive des cours d'eau. Sur la plus grande partie de son territoire, la particularité de la Guyane réside dans l'extraction aurifère (ou orpaillage) qui induit une perturbation des milieux aquatiques de nature à dégrader les eaux sur le plan physique (mise en suspension de sédiments) et chimique (contamination par les métaux lourds et les hydrocarbures). Ainsi, la plus grande partie du réseau hydrographique guyanais est potentiellement soumis aux effets de l'orpaillage.

3. Architecture de la Thèse

C'est dans le contexte à large spectre du changement global que s'est constituée la trame générale de cette thèse. En filigrane, il relie chacun des quatre chapitres traitant un thème particulier, tous relatifs aux milieux aquatiques continentaux. La figure 2, schématise l'organisation de la Thèse.

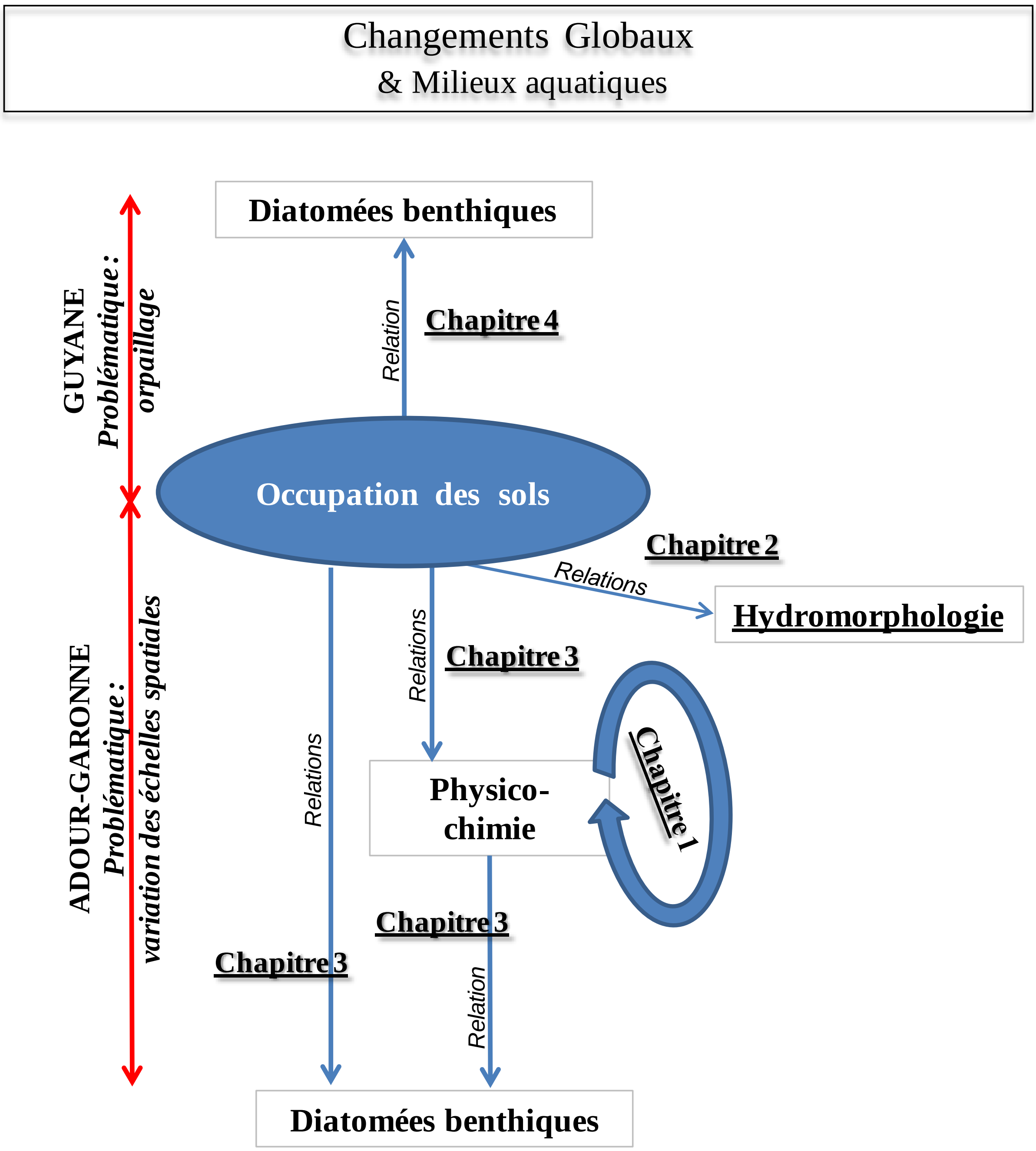


Figure 2. Représentation schématique des différents chapitres de la thèse.

Les trois premiers chapitres ont été réalisés dans le cadre du projet européen Euro-Limpacs du 6ème PCRDT et le quatrième dans le cadre du Programme CNRS-Nouragues (Projet Amazonie Phase 2). Les chapitres 2 et 3 ont été élaborés avec l'objectif de mise en relation des caractéristiques d'occupation des sols extraites à diverses échelles spatiales avec différentes métriques abiotiques et biotiques mesurées localement.

Le premier chapitre aborde l'aspect qualité chimique des eaux par le biais d'une étude portant sur l'évolution de la physico-chimie des rivières du bassin Adour-Garonne au cours de ces trois dernières décennies. En outre, par ses résultats cette étude temporelle établira une relation directe avec le changement climatique.

Le second chapitre traite le thème de la variation d'échelle spatiale de l'occupation des sols en relation avec l'hydromorphologie. Cette phase a pour objectif principal la détermination de la force avec laquelle s'établissent les relations entre les variables hydromorphologiques locales (définies au niveau des stations d'échantillonnage) et les patrons d'occupation des sols définis depuis l'échelle locale (proximité immédiate des stations) jusqu'à la totalité du bassin versant en passant par les échelles intermédiaires que sont le corridor fluvial et le sous-bassin versant.

Le troisième chapitre s'appuie sur le cadre conceptuel de la hiérarchisation spatiale et fonctionnelle des écosystèmes fluviaux. Les patrons d'occupation des sols extraits à différentes échelles spatiales ont été mis en relation avec des métriques relatives à la qualité de l'eau. Ces métriques de qualité correspondent à la fois à des variables physico-chimiques et de diatomées benthiques (indices diatomiques). Ainsi donc des relations directes (occupation des sols/physico-chimie et physico-chimie/diatomées) et des relations indirectes (occupation des sols/diatomées benthiques) ont été établies. L'objectif principal consistait alors à déterminer la force des liens entre ces trois métriques afin d'établir l'emprise spatiale d'occupation des sols la plus influente conjointement sur la physico-chimie et sur les diatomées benthiques.

Le quatrième et dernier chapitre se focalise sur le cas particulier du contexte guyanais pour lequel la pression majeure s'exerçant sur les milieux aquatiques est représentée par l'orpaillage. Cette dernière étude s'intéresse à la réponse des diatomées benthiques de petits cours d'eau forestiers face aux perturbations liées à l'orpaillage et tente d'apporter une réponse quant à leur utilisation potentielle comme indicateur biologique.

La conclusion générale est constituée de deux parties. La première est une synthèse des principaux résultats issus des analyses exploratoires de chacune des quatre études. La seconde partie propose des perspectives de recherche et de développement méthodologiques dans le cadre du suivi de la qualité des milieux aquatiques.

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CHAPITRE 1

Long-term changes in water physicochemistry in the Adour-Garonne hydrographic network during the last three decades

[Published] | Water Research

Changement temporel de la physicochimie des eaux du bassin hydrographique Adour-Garonne durant les trois dernières décennies

Résumé

Cette étude fait état d'une investigation portée sur la tendance des changements à long-terme de la physico-chimie des eaux douces du bassin Adour-Garonne (sud ouest de la France). Contrastant avec la plupart des études traitant de séries temporelles journalières, saisonnières ou annuelles, cette étude a analysé des données de trente ans concernant dix-neuf paramètres physico-chimiques relevés dans quarante-cinq stations. L'originalité de cette étude réside dans le traitement d'une importante base de données spatiale et temporelle. L'analyse statistique s'est faite à l'aide des réseaux de neurones artificiels à partir des moyennes annuelles de chaque variable. Les objectifs principaux consistaient à 1) déterminer les tendances des changements affectant la physico-chimie des eaux, 2) identifier les principales variables concernées et 3) discuter d'une récupération potentielle des milieux.

Cette analyse a mis en avant l'existence d'une zonation géographique du bassin en trois secteurs définie selon les changements les affectant :

i) un premier secteur comprenant les sites localisés dans les Pyrénées présente une grande stabilité chimique au cours du temps. Les eaux restent caractérisées par un haut degré d'oxygénation et des températures basses ;

ii) un second secteur qui s'étend du Piémont pyrénéen jusqu'aux zones estuariennes. Cette aire géographique est marquée par des changements majeurs concernant une hausse des teneurs en oxygène dans la zone de Piémont, une hausse des températures et une baisse des teneurs en azote et en phosphore pour les stations en plaine (de Toulouse aux zones estuariennes) ;

iii) un troisième secteur comprenant les sites localisés dans la zone estuarienne de l'Adour et de la Garonne marqué par une stabilité de la chimie au cours des trois décennies. Les sites de transition entre eaux douces et saumâtres ont montré des changements modérés relevant principalement d'une hausse des températures.

Deux contextes environnementaux sont en marge de ces tendances générales : les sites à haut degrés de contamination localisés dans les zones urbaines ou agricoles ne sont

concernés par aucun changement, pas même la température, et les sites localisés dans les zones karstiques essentiellement affectés par une forte baisse de la charge en phosphore.

Il est clairement apparu que le paramètre majeur contrôlant l'évolution des conditions environnementales et montrant le plus d'évolution au cours du temps est la température. La majorité des sites est concernée par l'effet du changement climatique. Les tendances générales mettent en avant le début de la hausse de la température de l'eau il y a une vingtaine d'années avec un réchauffement plus important durant la seconde décennie de l'étude (1984-1994). Les modifications des régimes thermiques sont généralement plus marquées dans la rivière Garonne, mais des tendances similaires sont également visibles au niveau des affluents.

Parallèlement, les deux dernières décennies sont marquées par une inflexion substantielle de la charge polluante et donc simultanément à une amélioration du statut trophique des cours d'eau. Dans de nombreux sites la charge en nutriments était plus faible entre 1995 et 2004. Cette tendance est confirmée par les suivis effectués par l'Agence de l'Eau Adour-Garonne qui a montré que 35% des stations étaient sujettes à la restauration de la qualité de leurs eaux, 61% restaient stables et 4% voyaient leur qualité décroitre. Ces résultats sont à mettre au compte d'un contrôle plus sévère des traitements des eaux usées malgré la croissance des pressions anthropiques.

Cette étude a montré que l'enrichissement en azote et la hausse de l'eutrophisation dans les hydrosystèmes sont des processus réversibles dans un laps de temps relativement court, de l'ordre d'une décennie. Quant à la hausse des températures, c'est elle qui représente le plus important et le plus complexe composant du changement global. Il est attendu que le long du continuum fluvial, le changement unidirectionnel de la température de l'eau conduise à une homogénéisation des hydrosystèmes et de fait à une réduction du gradient longitudinal.

Long-term changes in water physicochemistry in the Adour-Garonne hydrographic network during the last three decades

Loïc Tudesque, Muriel Gevrey, Gaël Grenouillet and Sovan Lek

Abstract

This study details a trend analysis covering a 30-year period (1975-2004) for 19 physicochemical parameters at 45 sites for surface waters in the Adour-Garonne basin in South-Western France. For statistical analysis, we used annual average of each variable. The analysis revealed sites affected by strong patterns of temporal variation and sites with weak or imperceptible changes of water quality. More than half the studied sites are affected by chemical changes. Trends were generally clearest in the River Garonne continuum, but similar tendencies can also be identified in tributaries. The overall trends point the onset of an increase of water temperature starting about twenty years ago and partial recovery from eutrophication during the last decade. As expected, the strongest trend affected the temperature regime of the hydrosystems, with warming which appeared to be more effective during the second decade of the study (1984-1994). Additionally, at many sites, nutrient loads were lower between 1995 and 2004, confirming a downward trend in eutrophication status resulting from more stringent control of sewage treatment despite the constant increase of anthropic pressure. Sites which did not present any trends are extreme sites located at each end of the river gradient: headwater and downstream sites under tidal influence. Other sites not affected by changes are those strongly perturbed by human activities showing a high level of degradation.

Keywords: artificial neural network; freshwater; Garonne; model of long-term change; time series; water quality.

1. Introduction

Clean water is a question of vital importance for the well-being of human societies. Damage caused to inland hydrosystems is one of the most serious environmental problems of the last century. Historically, rivers have been considered as a drainage channel for dilute pollutants and this behaviour has led to an inevitable increase of pollutant load. Water shortages are increasingly common and likely to become more severe in the future. Water shortages and poor water quality are linked since contamination reduces the supply of water and increases the cost of treating water for use (Carpenter *et al.*, 1998). There is a growing body of evidence that long-term changes are occurring in surface water chemistry in Europe and North America (Jenkins *et al.*, 2001). As a response to these environmental preoccupations, there is an obligation and strong political pressure for greatly increased emphasis on the control of pollution levels. It is along these lines that the recently agreed EC Water Framework Directive (European parliament, 2000) requires all inland water to reach "good ecological status" by 2015. The development of predictive capabilities for the management of streams implies taking the space and time scales into account (Minshall, 1988). Lotic ecosystems have developed in response to dynamic patterns and processes occurring along four dimensions; the fourth (time) imposes a temporal hierarchy on the three spatial dimensions of the river basin (Ward, 1989). Over the past two decades, interest in environmental temporal changes has resulted in numerous studies designed to monitor the physicochemical responses of a catchment. Hence, acidification, and the major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (HCO_3^-, NO_3^-, SO_4^{2-} and Cl^-) determining the ionic strength of surface water have been studied by many authors (Kopacek *et al.*, 2001; Harriman *et al.*, 2001; Moldan *et al.*, 2001; Bhangu and Withfield, 1997; Hutchins *et al.*, 1999). In addition, most hydrochemical studies seeking to identify stream water chemistry have been based on the headwater catchment scale (Smart *et al.*, 1998; Evans and Monteith, 2001). There are relatively few studies dealing with major river systems.

Over recent years, despite the water chemistry management and survey requirements, a growing interest in global warming has come to overlap any questions focusing on environmental changes. Global change is frequently considered as a major conservation threat, and recent studies have shown that it is possible to detect the effects of a changing climate on ecological systems (McCarty, 2001). There are a number of components of global environmental change of which we are certain – certain that they are going on, and certain that they are human-caused (Vitousek, 1994).

Actually, the requirements for large data resources, staff and time are clear reasons explaining why studies that have attempted to look at spatial and temporal variability for abiotic and biotic features of whole systems are apparently absent (Cellot *et al*, 1994). Working on a large scale provides a tool to study ecosystem response and to evaluate any physicochemical trends, including global change processes. Many underlying questions dominate the study of water quality on a large temporal scale: if the water quality changes over the time, is it improving or deteriorating? Which are the respective roles of the chemical and climatic changes? Quality monitoring of ecosystems is vital to determine whether variations in the water physicochemistry are leading to the desired improvements in the water quality of damaged systems. It is also necessary to develop scientific understanding and predictive models to support decision making on future pollution reduction.

The present study reports the results of an investigation into the trends in long-term changes (changes in overall means for decade time-series) in water physicochemistry in south-west France. In contrast with the numerous studies dealing with events on scales of days, seasons, and years (Minshall, 1988), the present study examines 30 years of water quality (19 physicochemical variables) at 45 sites over the Adour-Garonne basin, a major basin in France. The originality of the study is to gather a large temporal and spatial scale in the same data set. The main objectives, therefore, were (1) to determine the long-term directional changes in water chemistry, (2) to identify the major variables concerned and (3) to discuss any potential recovery that can be expected.

2. Materials and methods

2.1. Study area

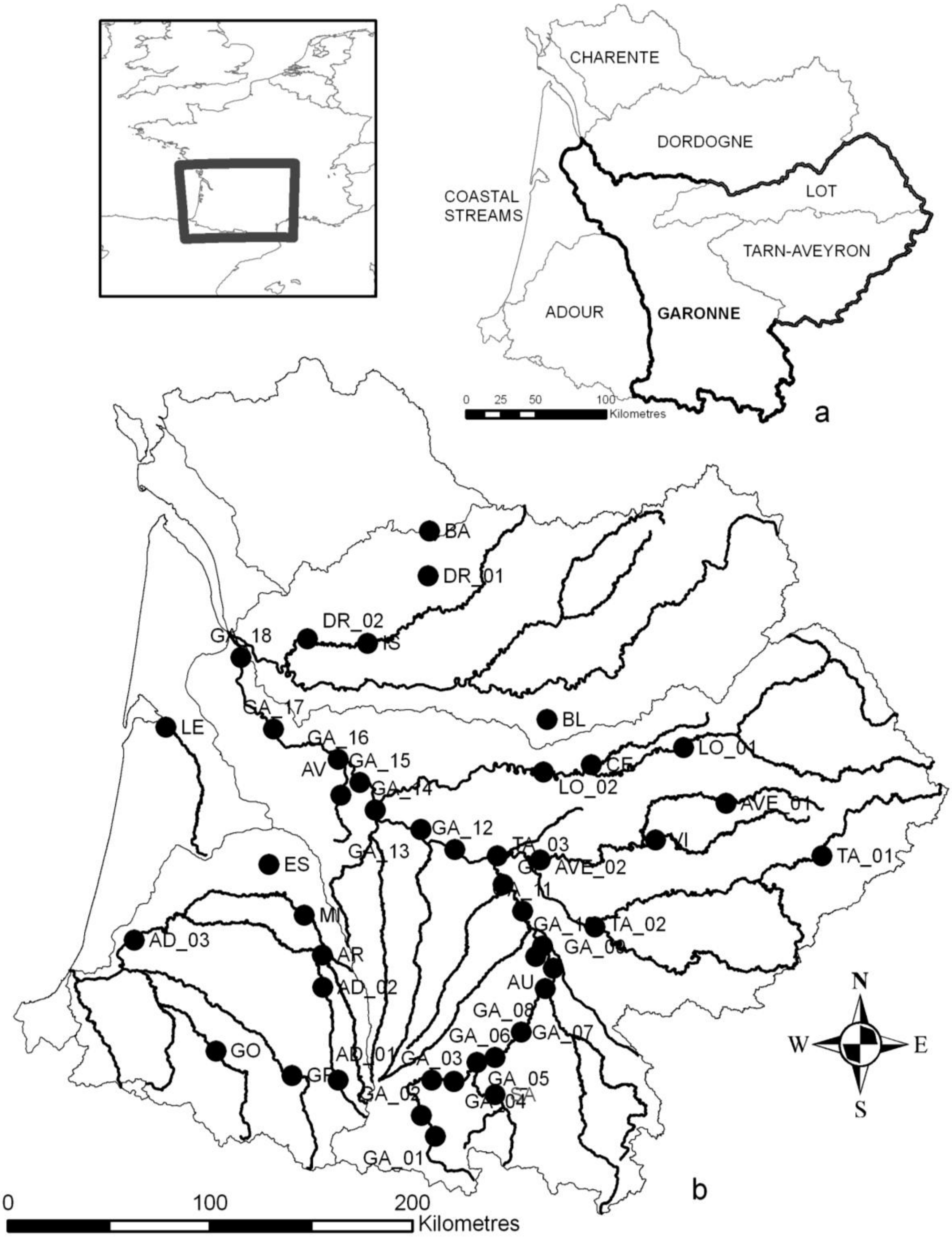
The Adour-Garonne hydrographic network covers south-west France in the Atlantic area. It extends over 116,000 km^2 from Charentes and Massif Central to the Pyrenees, gathering 120,000 km of watercourses including 68,000 km permanent rivers flowing into the Atlantic. The Garonne is the main channel, running over 580 km from the central Pyrenees in Spain to the Gironde estuary on the Atlantic coast. Its major tributaries come from the Massif Central plateau (Aveyron, Lot, Tarn) and minor ones from the Pyrenees range (The Gaves). The Adour-Garonne watershed covers a broad range of altitudes (high mountains to plains and coastal areas) and geological substrates: calcareous, sedimentary, sandstone, crystalline and volcanic (Tison *et al*., 2004). From south to northwest, topography and climate determine three great landscape types: the Pyrenees mountains with a pronounced relief, a vast green hilly zone of piedmont, and the valley of the Garonne river with flooding zones and alluvial terraces. The oceanic influence predominates over the whole basin, but lessens to the southeast with its Mediterranean influence, dry winds and lower rainfall (Mastrorillo *et al.*, 1998).

The geographical features, involving climate, geology and relief are summarised in the concept of hydroecoregion. This typology of aquatic ecosystems results from the implementation of the Water Framework Directive (Wasson *et al.* 2001). The basin covers 6 hydroecoregions, from South to North: Pyrenees (headwaters of the left bank tributaries of the Garonne), Côteaux aquitains (main floodplain), and limestone Causses; to the East: Grands Causses and Massif Central (headwaters of the right bank tributaries to the Garonne) and at the West with the coastal streams Les Landes (Fig. 1a). The catchment is vital as a regional water resource for drinking water, industry, irrigation and agriculture (35,000 irrigated farms) supplying over 6.5 million consumers. 30% percent of the population lives in rural areas, 28% in 35 towns of over 20,000 inhabitants. However Etchanchu and Probst (1988) considered that the Garonne basin is one of the least impacted by flow regulation in Europe and one of the least polluted. It has suffered from intensive damming and industrial impact during the second half of the 20th century (Steiger *et al.*, 1998) and the quantity of fertiliser applied has dramatically increased in the past few years (Semhi *et al.*, 2000).

2.2. Sampling sites

The data used in this work come from national water quality monitoring programmes (Réseau National de Bassin). The French hydrographic network is divided into six main basins and the south-western part is monitored by the Adour-Garonne Basin Water Agency (Agence de l'Eau Adour-Garonne). Thus, long-term monitoring of run-off chemistry over the three last decades in the Adour-Garonne basin recorded by the Water Agency provides a huge database for analysis of physicochemical trends. We focused our survey on 45 sites, including 18 along the longitudinal gradient of the River Garonne, gathering the longest and most complete temporal dataset collected since 1975. The temporal scale covers the last three decades, from 1975 until 2004. The sampling sites are distributed over the 7 main sub-basins: Adour, Charente, Dordogne, Garonne, Lot, Tarn-Aveyron and coastal streams (Table 1, Fig.

1a, b). Due to missing values in the series for some variables, the annual mean values of each variable were calculated. Then, it was decided to concentrate our work on three decades: the first from 1975 to 1984, the second from 1985 to 1994 and the third from 1995 to 2004. Mean values per decade were also calculated.



Figures 1*: Location of main sub-basins (a) and the Adour Garonne basin network with location of sampling sites (b) (for abbreviation, see Table 1).*

The 19 major physicochemical variables taken into account are: cations (NH_4^+, Ca^{2+}, K^+, Na^+), anions (HCO_3^-, Cl^-, NO_3^-, NO_2^-, PO_4^{2-}, SO_4^{2-}) and NH_3, pH, conductivity, Biological Oxygen Demand (BOD5), suspended mater, oxygen ($mg.l^{-1}$), oxygen saturation, air and water temperature.

Code	River	Site	Altitude	Code HER-1	HER-1	Relief	Geology	Climate
GA_01	GARONNE	Pont du Roi	580	1	Pyrénées	High mountains	Metamorphic granite	Moist mountain
GA_02	GARONNE	Chaum	479	1	Pyrénées	High mountains	Metamorphic granite	Moist mountain
GA_03	GARONNE	Valentine	364	1	Pyrénées	High mountains	Metamorphic granite	Moist mountain
GA_04	GARONNE	Labarthe Inard	321	1	Pyrénées	High mountains	Metamorphic granite	Moist mountain
GA_05	GARONNE	Boussens	260	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GA_06	GARONNE	Cazères D7	233	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GA_07	GARONNE	Marquefave	191	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GA_08	GARONNE	Pinsaguel	150	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GA_09	GARONNE	St-Pierre	131	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GA_10	GARONNE	Gagnac	119	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GA_11	GARONNE	Verdun	96	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GA_12	GARONNE	Lamagistère	52	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GA_13	GARONNE	Aqueduc	40	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GA_14	GARONNE	St- Léger	37	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GA_15	GARONNE	Mas d'Agenais	17	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GA_16	GARONNE	Couthures	16	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GA_17	GARONNE	Cadillac	6	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GA_18	GARONNE	Bordeaux	4	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
AD_01	ADOUR	Pouzac	505	1	Pyrénées	High mountains	Metamorphic granite	Moist mountain
AD_02	ADOUR	Estirac	164	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
AD_03	ADOUR	Dax	5	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
AR	ARROS	Tasque	120	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
AU	AUSSONNELLE	Cornebarieu	140	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
AV	AVANCE	Plantey	48	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
AVE_01	AVEYRON	Ampiac	490	3	Massif central Sud	Mountains	Metamorphic granite	Moist mountain
AVE_02	AVEYRON	Loubéjac	75	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
BA	BANDIAT	Villejaleix	141	9	Tables calcaires	Plains	Sedimentary limestone	Temperate oceanic
BL	BLEOU	Gourdon	170	11	Causses aquitains	Mild relief	Sedimentary limestone	Meridional oceanic
CE	CELE	Cabrerets	165	11	Causses aquitains	Mild relief	Sedimentary limestone	Meridional oceanic
DR_01	DRONNE	Valeuil	99	11	Causses aquitains	Mild relief	Sedimentary limestone	Meridional oceanic
DR_02	DRONNE	Coutras	4	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
ES	ESTAMPON	Roquefort N132	62	13	Landes	Plains	Detritus	Meridional oceanic
GO	GAVE OLORON	Oloron	211	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GP	GAVE PAU	Rieulhes	342	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
GI	GIMONE	Lafitte	84	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
IS	ISLE	Bénevent	35	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
LE	LEYRE	Facture	6	13	Landes	Plains	Detritus	Meridional oceanic
LO_01	LOT	Livinhac	194	3	Massif central Sud	Mountains	Metamorphic granite	Moist mountain
LO_02	LOT	Douelle	112	11	Causses aquitains	Mild relief	Sedimentary limestone	Meridional oceanic
MI	MIDOUZE	Laujuzan	79	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
SA	SALAT	Caumont	358	1	Pyrénées	high mountains	Metamorphic granite	Moist mountain
TA_01	TARN	Millau	360	19	Grands causses	Mountains	Sedimentary limestone	Sub-mediterranean
TA_02	TARN	Rabastens	101	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
TA_03	TARN	Moissac	65	14	Coteaux aquitains	Mild relief	Detritus	Meridional oceanic
VI	VIAUR	La Garde	195	3	Massif central Sud	Mountains	Metamorphic granite	Moist mountain

Table 1: *Location and characteristics of sampling sites*

2.3. Data analysis

We used the method of Self-Organising Maps (SOM) which is an unsupervised algorithm of artificial neural network model (Kohonen, 1982). SOM is an efficient method for analysing systems ruled by complex non-linear relationships and provides an alternative to traditional statistical methods for classifying complex data (Lek & Guegan, 2000; Park et al., 2003a). Successful results in aquatic ecology using such models have been well documented (Chon et al., 1996; Park et al., 2003b; Gevrey et al. 2004). SOM is used to classify the samples such that similar sites with close chemical values are organized as neighbours on a map. The SOM neural network consists of two layers of neurons: the input layer and the output layer. The output layer is represented by a map or a rectangular grid with l by m neurons (or cells), laid out in a hexagonal lattice. The principle is to classify the sample vectors (*SV*) described by a set of descriptors on the map according to the similarities between the descriptors. Two *SV* which are similar (from a descriptor point of view) are classified in the same cell of the map or in neighbouring cells while two different *SV* are classified in separate cells distant the one from the other.

The sequential SOM algorithm used in this study can be summarised as follows (see Kohonen 1995 and Giraudel and Lek 2001 for more details):

- The virtual vectors (VV_j, $1 \leq j \leq c$) are initialised with a random sample drawn from the input dataset.
- The *VVs* are updated in an iterative way.
  - A sample vector (SV_k) is randomly chosen as an input vector.
  - The Euclidean distance between this SV_k and each *VV* (each cell) is computed.
  - The *VV* closest to the SV_k is selected and called "best matching unit" (*BMU*).
  - The *BMU* and its neighbours are moved slightly towards the SV_k using this rule: $VV_j(t+1) = VV_j(t) + \eta(t) \cdot N(t,r)(SV_k(t) - VV_j(t))$

Where t is the number of iterations, $SV_k(t)$ is a sample vector, in other words, $SV_k(t)$ is a vector of the values of the input neurons at iteration t, $VV_j(t)$ is a virtual vector that represents the weights between a neuron j of the output layer and all the neurons of the input layer at iteration t, $\eta(t)$ is the learning rate that is a decreasing function of iteration t, and $N(t,r)$ is the neighbourhood function with r representing the distance in the map between the winning neuron and its neighbouring neurons. This function defines the size of the neighbourhood of the winning neuron (*BMU*) to be updated during the learning process. This learning process is continued until a stopping criterion is met, usually when weight vectors stabilize or when a number of iterations are completed. At the end of the learning process, the BMU is determined for each site, and each site is associated with the corresponding cell of the map.

In this study, the *SV* are represented by the sites for each decade (3 per site) described by the chemical variables. The input layer then comprised 19 neurons connected to 135 samples (i.e. 135 *SV*). The output layer comprised 70 neurons organised in an array with 10 rows and 7 columns. This number of neurons was defined according to a compromise between the formula $c = 5\sqrt{n}$ proposed by the laboratory of Computer and Information Science (CIS), Helsinki University of Technology (2000), where *c* is the number of cells and *n* is the number of training samples (sample vectors) and the computation of the topographic and quantization errors, two evaluation criteria to quantify the resolution and topology preservation**.** The software package for the SOM method is available and freely downloadable from the website : http://www.cis.hut.fi/projects/somtoolbox/.

Additionally, in order to define boundaries between possible subsets existing in the map (regrouping cells similar enough to be in the same cluster), a hierarchical cluster analysis with the Ward linkage method is applied to define the cluster boundaries in the units of the SOM map according to the similarities of the *VV* of the output neurons.

To analyse the contribution of each descriptor (chemical variables) to structure the trained SOM, each descriptor and the connection weight calculated for each virtual vector during the training process can be visualized in grey scale on the SOM map. A map can then be visualised separately for each descriptor.

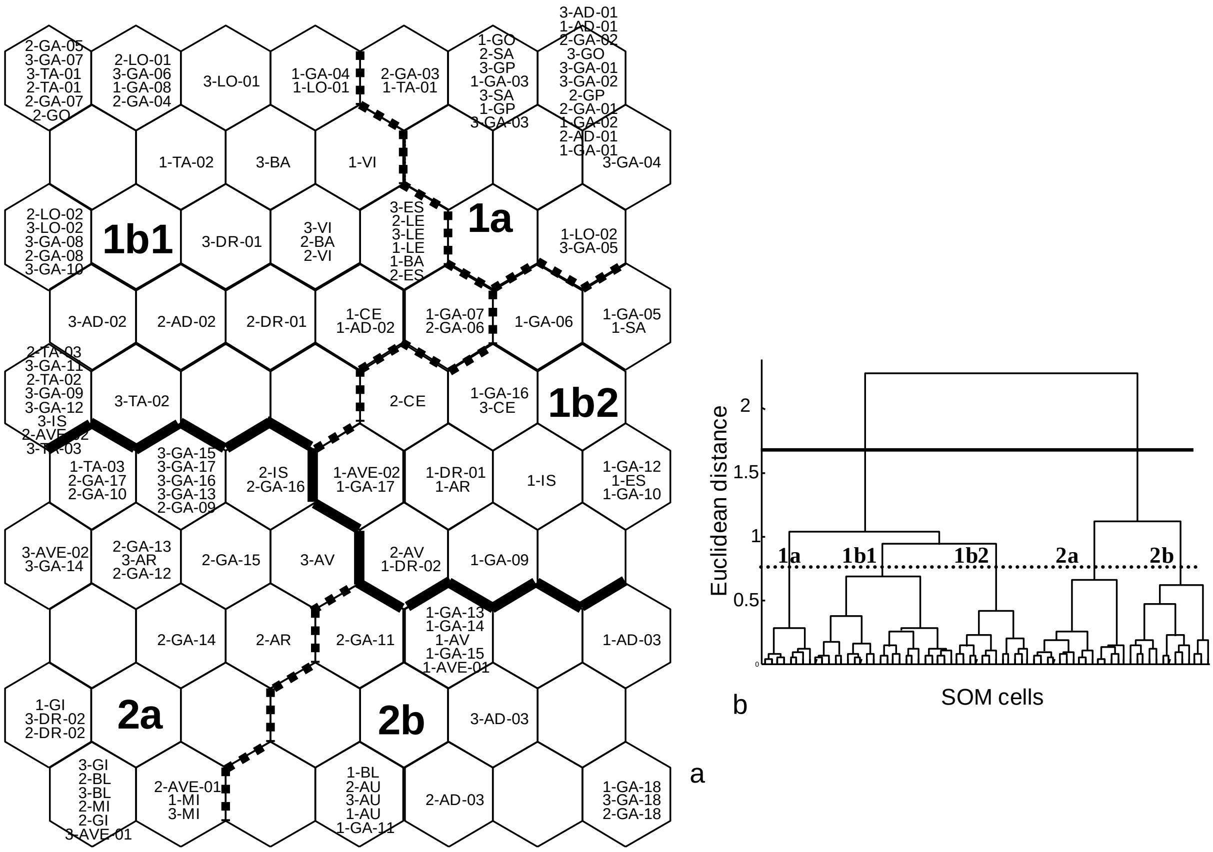
3. Results

Trends were modelled on the data set at 45 sampling sites distributed all over the Adour-Garonne basin over the 1975-2004 period split into 3 subsets: 1975-1984, 1985-1994 and 1995-2004. A mean value of 19 physicochemical variables was used for each decade. Sampling sites for each decade where classified through the learning process of the SOM according to the chemical variables, and a SOM map was established for each variable.

3.1. Spatial trends

The sampling sites were first classified on the SOM map according to their similarity by physicochemical characteristics (Fig. 2). Different map sizes were tested and we chose the optimum map size of [10 x 7] based on the minimum values of quantization (0.383) and topographic errors (0.06). The distribution of the sites over the map appears to be heterogeneous with lumps located in the top left and right corners, the left centre and in the bottom left corner.

Based on similarity between SOM cells (i.e. virtual units), five clusters of samples were identified (Fig. 2). These distribution patterns showed the characteristics of longitudinal key conditions of water systems, from the head of the basin at the top (cluster 1) to the downstream area at the bottom of the SOM map (cluster 2). Cluster 1a is mainly from the head of the Adour and Garonne basins at high altitudes. Cluster 1b1 is mostly from the head of Lot and Tarn in the lower altitude mountains in the Massif-Central and the piedmont zone of Adour-Garonne. Cluster 1b2 is characterised by sites only represented by the first decade. Cluster 2 is from downstream areas, affected more or less strongly by eutrophication. The 2b sites are located in brackish zones.



***Figures 2**: Classification of sampling sites based on similarities from a physicochemical point of view on the SOM output layer. The acronyms in the hexagonal units represent the different sites, and are shown in Table 1. Numbers before acronyms (1 to 3) mean first, second and third decade. There are five clusters in total: two main clusters 1 and 2 with subclusters (1a, 1b1, 1b2, 2a and 2b). b) Location in the SOM map of the 5 clusters defined by a clear physicochemical tendency, according to the similarity between SOM cells after model training.*

A map was drawn for each physicochemical variable to define the contribution of each to building up the site map (Fig. 3). Except for the pH, each physicochemical variable displays a high gradient distribution. Dark areas represent high contributions of the variables to the construction of the map, and light ones exhibit low values. According to the contribution of the input variables, the SOM map proposes five major gradients corresponding to main clusters in Fig. 2: (1) Oxygen concentration (O_2 mg.l^{-1}) is characteristic for cluster 1a. The value varies from the bottom to the left or to the right top corner (a gradient of oxygenation); (2) cluster 1b1 is mainly determined by high values of oxygen saturation, air temperature and pH; (3) while cluster 1b2 is determined by high Biochemical Oxygen Demand (BOD5); (4) in cluster 2a water temperature, bicarbonates, calcium and nitrates are the major determinants; (5) cluster 2b is characterized by reduced nitrogen, chlorine, suspended mater, natrium and sulphate. Conductivity and potassium are specific parameters for clusters 2a and 2b.

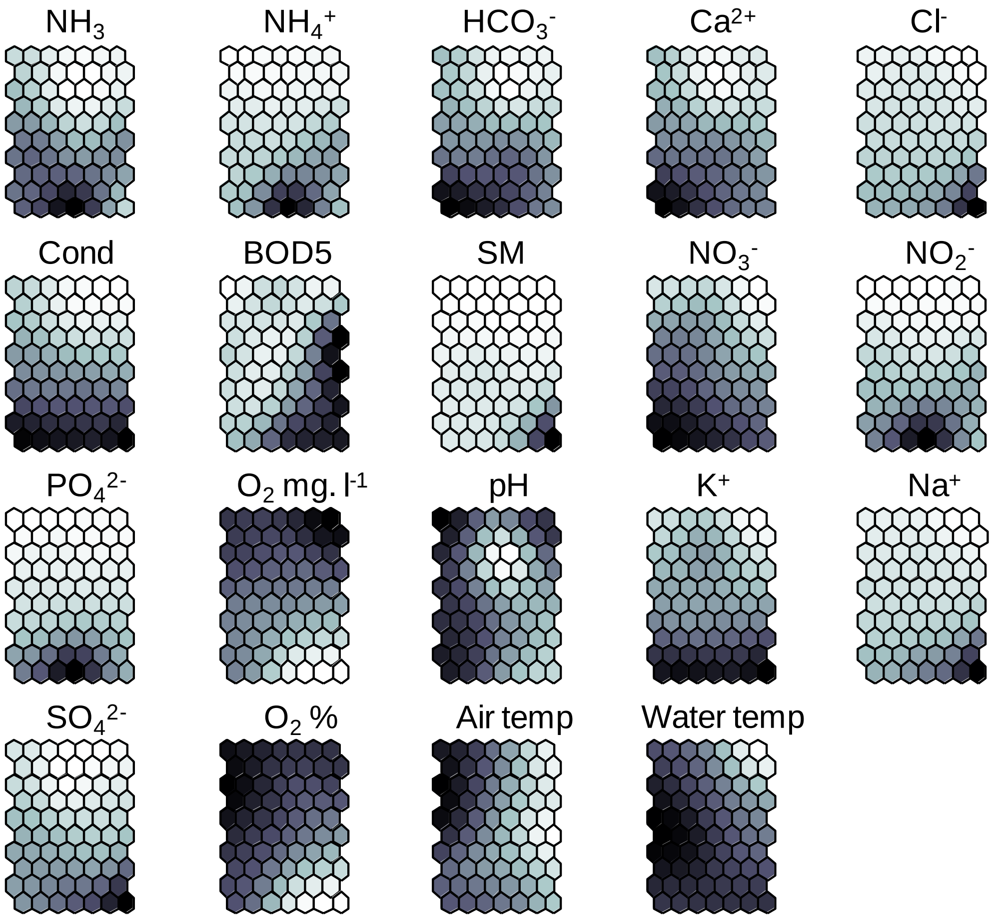
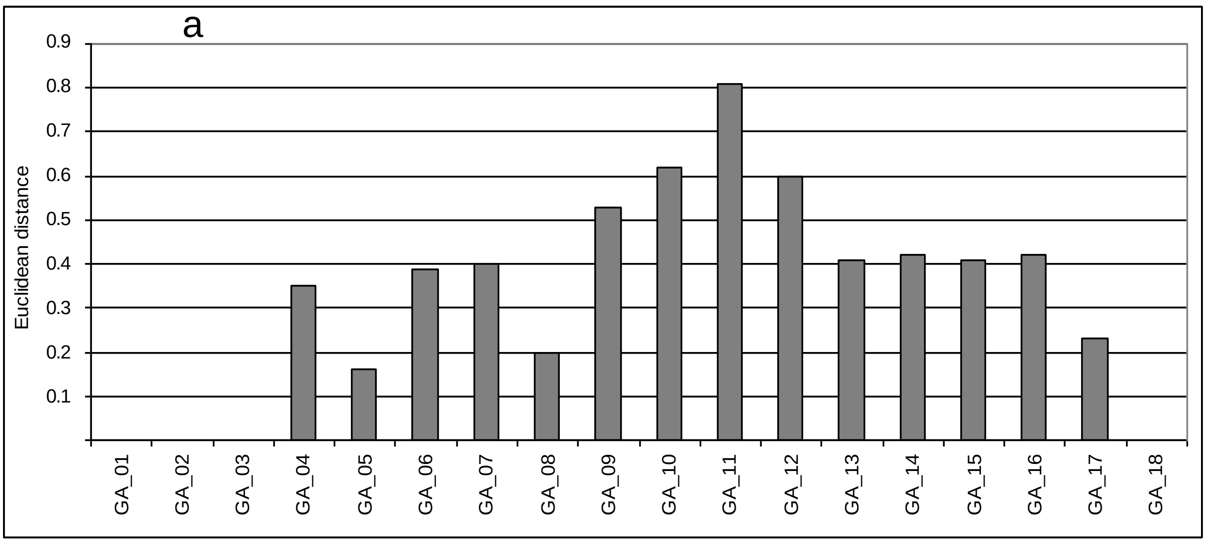
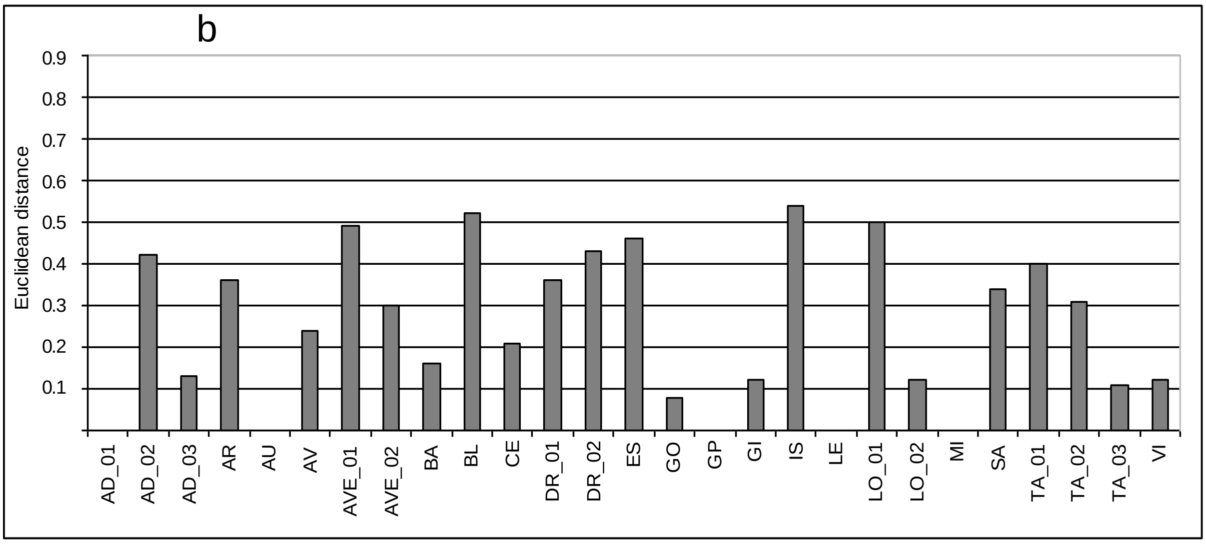


***Figure 3**: Maps of each descriptor displaying the contribution of the 19 environmental variables of sampling sites. Dark areas represent high values of each input variable, while light ones are for low values.*

The Euclidean distance for the same site between the SOM cell where the site corresponding to the first decade has been plotted and the SOM cell where the site corresponding to the last decade has been plotted was computed. All the distance calculated for each site were represented graphically. In Fig. 4a with all sites except the River Garonne and Fig. 4b for the Garonne continuum sites, where sites are in abscise and Euclidean distance in ordinates, the higher the bar plots are and more the sites are concerned by important physicochemical changes. As complement to obtain a better spatial understanding of the change extent, we transposed the Fig. 4a and Fig. 4b onto a geographic map representation (Fig. 5) were bar plots are converted into spots. We defined colours gradient from white to black with 5 classes, more important the Euclidean distance is and darker the spot is. These changes show different scales of magnitude leading to patterns of spatial distribution over the basin. Sites with minor changes (Euclidean distance < 0.24) represent almost half the study sites (21/45). They are broadly distributed throughout the basin, nevertheless some trends are apparent. The sites mainly seem to be located upstream in the Pyrenean headwaters, in the coastal and estuary zones. Seven sites are strongly affected by chemical changes (Euclidean distance > 0.5), 4 of them are located in the middle part of the Garonne continuum in Toulouse suburb, and the 3 others are in the North part of the basin. 2 sites (LO_02 and BL) are in the "Causses aquitains" and one site (IS) in the North of "Coteaux aquitains". A group gathering 17 sites affected by moderate changes (Euclidean distance between 0.25 and 0.5) is spread all over the basin without any evident pattern of distribution.





***Figures 4**: Bar plot of Euclidian distance between SOM cells for the Garonne continuum sites (a) and the other sites (b).*

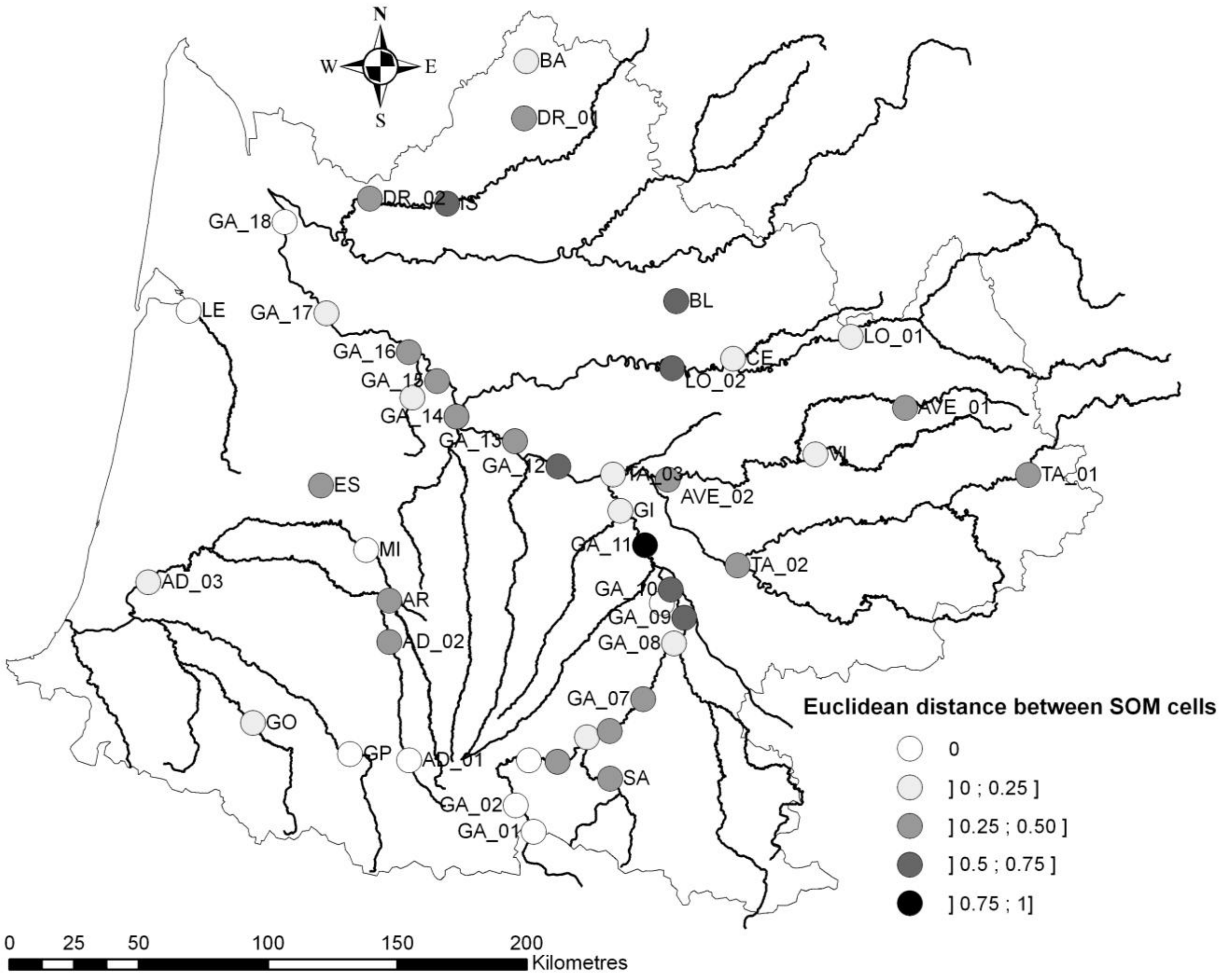


***Figure 5**: Geographic map representation of the temporal trends of the water chemistry based on the Euclidean distance between the SOM cells.*

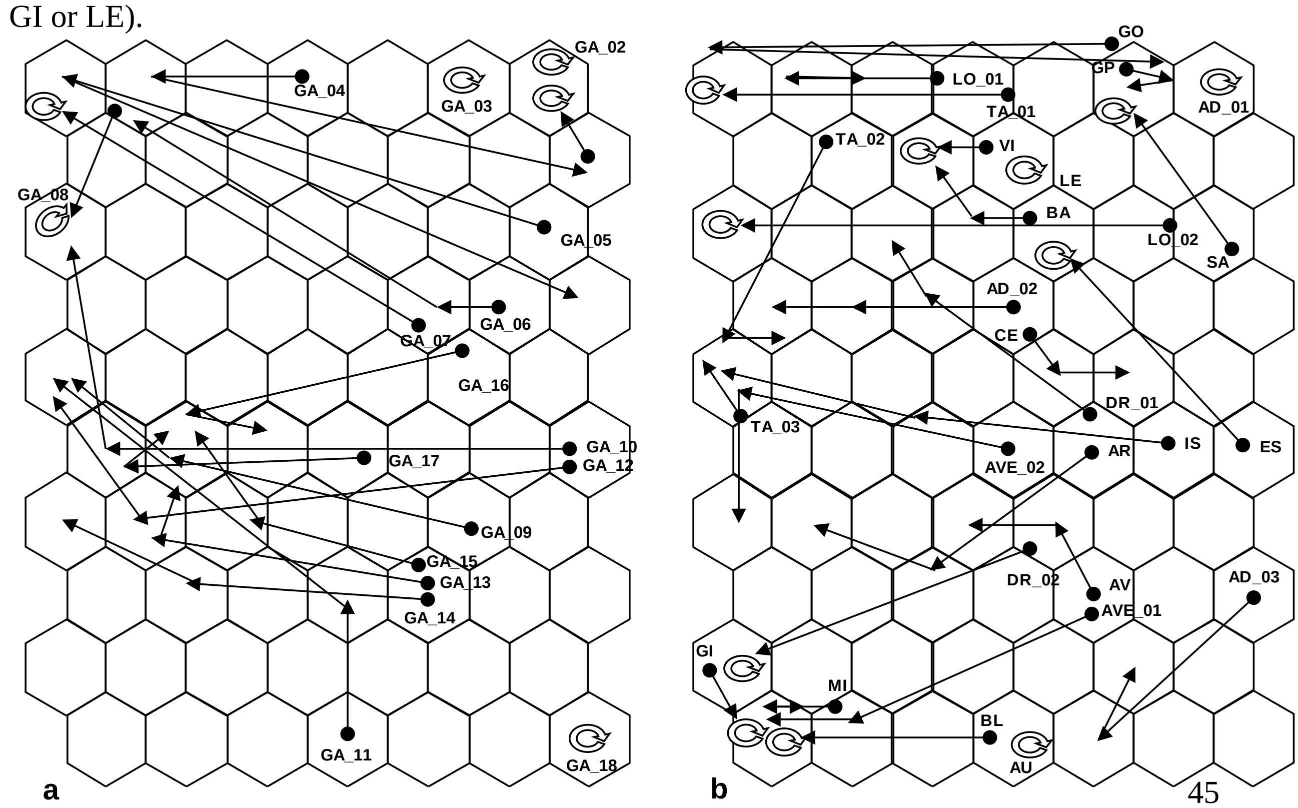
3.2. Temporal changes

Jointly with physicochemical changes leading to a spatial distribution pattern, temporal stages are obvious. By superimposing the sampling sites and physicochemical parameters on the SOM map, general trends of physicochemical parameters can be revealed during the last three decades for the Garonne continuum (Fig. 6a) and its tributaries (Fig. 6b).

Depending on these temporal shifts of the sites on the SOM map, the chemical trends are presented in two ways:

- first, during the last three decades, numerous sites moved in one major direction, except for sites GA_05 and GO. Of the 45 sites, 25 are affected by a shift mainly directed to the left side of the map (11/18 sites for the Garonne river), corresponding to the global air and water temperature gradient. In this fist group, gathering more than half the sites, we can separate three sub-groups (below we give a few examples): i) a group of sites shifting from the right to the left centre - GA_09, GA_12, GA_15, AD_02 or IS - **,** ii) some sites moving from the right to the left top corner - GA_06, GA_07, GA_10 or TA_01- and iii) sites evolving from the right bottom to the left bottom corner (DR_02, AVE_01 or BL). Respectively, these directions correspond to increasing water temperatures, oxygen and eutrophication gradients. We have to note that only one site (GA_04) presents an original pattern sliding to the right side;

- second, a group of 20 sites did not show any significant shift (GA_01, GA_02, GA_18, BA, GI or LE).



Figures 6*: Temporal representation of the sampling site shift in the SOM map during the last three decades for (a) sampling sites along the Garonne continuum and (b) the other sites located over the Adour-Garonne basin. The point positions the first decade, the first arrowhead the second and the second arrowhead the last decade. Thus, each arrow represents the shifts occurring in a site during one decade. The circular arrow means that there is no change of site within the cell. For acronyms, see Table 1.*

The aspects noted above describe an overall view of the chemical trends over three decades. Nevertheless, it is necessary to point out how these events occurred in time. The diagram of temporal representations of the sampling sites shifting in the SOM map stresses the importance of the first arrow representing the evolution between the first and second decade. Actually, 21 sites present a major shift from the first to the second decade, and then transition to the third decade is slowed down or stopped (circular arrow), for example this is the case for sites GA_07_09_10_12, ES or LO_02. A group of 3 sites shows major changes during the transition between the second and third decades (GA_04, GA_06 and GA_11). Only one site (IS) is characterised by a “linear” change between decades; the two arrows present more or less the same amplitude range.

When chemical changes occurred with time, they were not linear. Actually, most of the sites concerned by changes were affected during the transition between the reference decade (1975-1984) and the second decade (1985-1994). During the last ten years (third decade 1995-2004) the physicochemical changes appear to have slowed down or stopped suggesting that the river systems will tend towards a new balance of physicochemical status.

4. Discussion

Along the River Garonne continuum, 3 distinct homogenous sections, with transitional stages, are defined according to the chemical changes occurring. Changes in many sites located on the Garonne tributaries can also be gathered under these different headings.

i) Sites located upstream in the Pyrenees Mountains show a great chemical stability over time, thus without any kind of trend. The physicochemistry remains mainly characterized by a high level of oxygen and low temperature. Sites of the headwater of the Adour River present the same chemical pattern with a general absence of trend.

ii) The second section, and the major one, extends from the piedmont to sites not under tidal influence. All these sites are affected by marked chemical changes. Two sub-groups are apparent: 1) sites from piedmont to plain characterised by a high level of oxygen show an increase of this parameter since twenty years ago. In some of them, both an increase in oxygen saturation and in air temperature occurred; 2) 8 sites from Toulouse suburb to the tidal zone are affected by major chemical changes over the two last decades. It appears that the trends are mainly towards an increase in air and water temperature and also towards a decrease of phosphorus and nitrogen load. Moreover, many sites located on the Garonne tributaries are concerned by changes in water temperature. Nevertheless, these sites, on the Garonne continuum, did not show any evident improvement of eutrophic status.

iii) sites located in tidal zones have conserved chemical stability during the last decades, that is the case for the Garonne and Adour estuary. We observe that the site at the transition between brackish water and freshwater shows moderate changes relating to an increase of water temperature.

In parallel with these general tendencies described above along the Garonne continuum, some complements of changes in water physicochemistry have been identified in different local environmental contexts (geology, land-cover) without any kind of spatial distribution. These events are described below:

- sites with high level of pollutant compounds did not show any major changes in their water chemistry over the last twenty years, nor in temperature. These sites are located in cities suburbs or in agricultural areas;

- some sites located in or draining calcareous areas presented similar patterns and seem to be affected by a strong decrease of phosphorus load.

It clearly appears that the predominant parameter controlling the evolution of the environmental conditions and showing major adjustments over time is the temperature. The majority of the sites were affected in this way. Thirty years of extensive physicochemistry data show that coherent warming occurred in Adour Garonne rivers and streams, reflecting global changes. There are currently numerous climate scenarios produced by various global climate models (Allen *et al.*, 2000), but most model predictions for northern Europe do imply significant increases in air temperatures over the next 50-100 years (Benestad, 2002). In recent years, climate change has been identified as an important source of aquatic disturbance and can be considered as thermal pollution on a large to global scale (Mohseni and Stefan, 2001, Stefan *et al.*, 2001). Nevertheless, few long-term data sets are available to enable the implications of this climate change to be studied (Caissie, 2006) and could led to contradictions. Webb and Nobilis (1997) carried out a long-term study, in which they analysed 90 years of water temperature data from north-central Austria. No specific trends were reported in water temperatures in this long-term study. In contrast in 1994 the same authors reported a significant increase of 0.8°C over a similar time period in the River Danube and attributed the increase mostly to human activities. Increases in water temperature over a 30-year period were also observed in Scotland. Hari *et al.* (2006) concluded in their study about Alpine rivers and streams of Switzerland that during the last quarter of the 20th century, substantial stream warming occurred, most of which can be attributed to an abrupt increase in temperature. In the analysis of the water temperature of the Loire for the period 1976-2003, Moatar *et al.* (2006) show a change in the energy regime with very significant rises in spring and summer (from 1.5 to 2°C).

Parallel to this, during these last two decades, a second substantial tendency is the decline of pollutant loading and jointly the trophic condition. In the present study, on the base of the statistical analyses of the chemical data-set, it seems that nutrient enrichment exhibits a noticeable decrease. This tendency is corroborated by the assessments and the survey carried out by the Adour Garonne water agency. The river quality improved at 35% of the survey sites, 61% remained stable and only 4% showed significant degradation. Indeed, the depolution effort has been increasing since the 1980's. Between 1971 and 1997, for all pollutant compounds (organic matter, suspended matter) water quality is improving in spite of increased industrial. In the 1980's, only 30 to 36% of mineral organic and toxic pollution in effluent from built-up areas and industry were treated. The clean-up rate of the Adour-Garonne basin built-up areas from 35 % at the end of 1991 reached 46.5% in 1997. It should however be noted that this progression, started well in 1992, 1993 and 1994, has tended to slow down since 1995. In 2004, 57% of urban pollution was eliminated in the basin (Agence de l'Eau, 1984, 1996, 1999 and 2006). This trend has also been followed in other large French rivers. Lair (2001) showed, in Middle Loire, a decrease of the phosphate fluxes, which suggests that catchment area treatments performed by Water Agency authorities were successful.

In contrast, Wright *et al.* (2001) in a study about trends in nitrogen deposition in streams across Europe concluded that few of the sites exhibit significant long-term trends in nitrate concentration. Stoddard *et al*. (1999) and Skjelkvale *et al.* (2001, 2005) did show significant trends in nitrate concentration, consisting of a universal increase largely restricted to the 1980s, followed by reversal of NO_3^- trends in the 1990s, especially in north/central Europe and North America. Jackson *et al.* (2001) concluded that freshwater eutrophication and pollution decreased in many waterways.

The global nitrogen cycle has been altered by human activity, and increased nitrogen input has altered the chemistry of the aquatic ecosystem and contributes to eutrophication. In 1994, Vitousek concluded in a study dealing with Ecology and Global change, that the global nitrogen cycle altered by human activity probably currently presents the most important component of global change and will do for some decades to come. In the present study, as well in recent studies dealing with global change, it has been shown that nitrogen enrichment and increase of eutrophication in hydrosystems could be a reversible process in over short time scale of one decade.

5. Conclusion

The distinctive feature of this study is that it concerns physicochemical data covering a long spatial and time scale, contrasting with previous analyses dealing with shorter scales. The results show clear and widespread evidence of changes affecting the chemistry of watercourses in the Adour-Garonne basin. More of half of the sites studied were found to be undergoing change. Trends are generally clearest in the River Garonne continuum, but many of the same trends can also be identified in tributaries.

The overall pattern of change particularly involves the onset of an increase in water temperature which has been occurring for the last twenty years and the recovery from eutrophication during the last decade. As would be expected, strongest trend affects hydrosystems in their temperature regime: the warming seems to be more effective during the second decade of the study (1984-1994). Additionally, at many sites nitrogen and phosphorus load were lower between 1995 and 2004 confirming a downward trend in eutrophication status resulting from the efforts made in sewage treatment works despite the constant increase of anthropic pressure. Sites that did not present any such trends are at the extremes located at either end of the river gradient: headwater and tidal zones. Other sites unaffected by changes are those strongly disturbed by human activities showing a high level of eutrophication. Here, any minor changes would not be perceptible.

We are in the midst of one of the largest experiments in the history of Earth, where human effects on climate, biogeochemical cycles, and land use are having important consequences on the ecosystem (Chapin *et al*., 2000). Whereas eutrophication of aquatic systems seems to be a reversible process on a short time-scale, global warming represents the most important, complex and underestimated component of global change. Scheffer *et al*. (2001) mentioned that all ecosystems exposed to gradual changes assumed a response in a smooth way, but which can be interrupted by sudden drastic switches preceded by a loss of resilience. In a river continuum, this unidirectional change in water temperature should lead to the homogenisation of the hydrosystem regime and flatten the river gradient. The headwaters, within natural or near-natural conditions without any perceptible change, constitute suitable sensors of changes and should be considered as milestones to survey and assess any adjustment occurring in freshwater. It is along these lines that the European Water Framework directive (European parliament, 2000) encourages the assessment, maintenance and restoration of good ecological status. Hence, distinguishing natural ecological conditions paves the way for implementing the directive. Taking temperature as a predominant parameter in ecology investigation could be determinant in terms of policy to regulate and assess reversibility of ecological status. The next step will be to gather long-term biological series to evaluate the effects of physicochemical changes on the community structure of different trophic web components.

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CHAPITRE 2

Links between stream reach hydromorphology and land cover at different spatial scales in the Adour-Garonne Basin (SW France)

[Accepted] | Knowledge and Management of Aquatic Ecosystems

Relations entre les caractéristiques hydromorphologiques de section de cours d'eau et l'occupation des sols extraite à différentes échelles spatiales dans le bassin Adour-Garonne (S-O France)

Résumé

L'hydromorphologie tient une place centrale parmi les différentes composantes des hydrosystèmes ; c'est elle en particulier qui définit les paramètres de l'habitat auxquels est soumise la biocénose. Les caractéristiques hydromorphologiques constituent un cadre physique à travers lequel les interactions biotiques et abiotiques s'organisent. Les rivières étant des systèmes hiérarchisés avec des niveaux d'organisation spatiale imbriquée, il devient alors essentiel d'identifier l'échelle spatiale des différents patrons du paysage la plus influente sur les conditions du milieu.

Nous présentons les résultats d'une étude dont l'objet consiste à examiner les relations qui lient l'occupation des sols (O.S.) à l'hydromorphologie d'une portion de cours d'eau, et particulièrement à identifier l'échelle spatiale pour laquelle l'emprise de l'O.S. est la plus déterminante. Afin de répondre à cet objectif, l'analyse a été menée en 4 étapes :

1) établissement d'une typologie des sites sur la base de leurs caractéristiques hydromorphologiques ;

2) prédiction de la typologie à partir des variables d'O.S. et identification de l'importance de chacune des échelles ;

3) examen de la contribution des variables explicatives de l'O.S. ;

4) détermination des liens entre les variables hydromorphologiques et les variables d'O.S. pour les différentes échelles spatiales.

Cette étude a été conduite dans cent quatre stations du bassin Adour-Garonne. Vingt-sept variables d'hydromorphologie ont été relevées dans chacune des stations. L'occupation des sols a été extraite selon cinq emprises spatiales et trois grains différents de Corine Land Cover (classes et sous-classes). Après classification des stations pour déterminer la typologie, l'analyse statistique s'est faite en utilisant la technique de modélisation des « Random Forests ».

Premièrement, il a été mis en évidence une typologie des sites d'étude montrant un gradient amont/aval structuré à la fois par les descripteurs géographiques et les caractéristiques hydromorphologiques des bassins versants. Deuxièmement, il est démontré que les relations entre l'hydromorphologie et les différentes échelles spatiales répondaient également à un gradient longitudinal. Dans les zones amont, aucune différence notable n'a été observée quel que soit le type d'O.S. considéré, alors que dans les zones aval, les larges échelles spatiales étaient plus étroitement reliées à l'hydromorphologie. Troisièmement, il a été observé un effet spécifique de l'O.S. sur chaque type hydromorphologique. Le long du gradient, la contribution des variables d'O.S. structurant les types d'hydromorphologie décroit pour ensuite devenir homogène. Quatrièmement, les relations les plus fortes ont été établies entre les variables hydromorphologiques et les variables d'occupation du sol pour les échelles les plus larges.

Cette étude apporte des informations pertinentes en accord avec les demandes de la Directive Cadre Européenne prônant une gestion durable de l'environnement. Dans le contexte de conditions naturelles, nous recommandons de prendre en compte prioritairement l'échelle du bassin versant lorsque des connexions sont établies avec l'occupation des sols ; l'environnement local ou rivulaire étant complémentaire dans le cadre de sites impactés.

Links between stream reach hydromorphology and land cover at different spatial scales in the Adour-Garonne Basin (SW France).

Loïc Tudesque, Muriel Gevrey, Gaël Grenouillet and Sovan Lek

Abstract

We report an investigation aimed at improving the understanding of the relationships between hydromorphology and land cover, and in particular aimed at identifying the spatial scale at which land cover patterns best account for the hydromorphology at a stream reach.

This investigation was carried out in the Adour-Garonne basin. Several key findings emerged from the use of new modeling procedures called “Random Forests”. Firstly, we established a typology of sites showing an upstream/downstream gradient structured by geographical descriptors and catchment hydromorphological features. Secondly, we found that the relationships between hydromorphology and the different spatial scales of land cover responded to a longitudinal gradient. Upstream, no noticeable difference was observed whatever the land cover pattern considered, whereas downstream, larger scales were strongly related to the hydromorphology. Thirdly, a specific land cover effect on each hydromorphological type was seen. Along the gradient, the contribution of the land cover variables structuring the hydromorphological types decreased and become homogenous. Fourthly, stronger correlations were established with individual hydromorphological variables using the larger scales of land cover. This paper contributes to a better understanding of landscape ecology and fits well with the European Water Framework Directive that requires long-term sustainable management. In the context of natural condition, we advise that catchment scale should be given high priority when connected with land cover/uses; local and riparian environment being more valuable and complementary in the case of impacted sites.

Keywords: hydromorphology; land cover; spatial scale; Random Forests; stream

1. Introduction

Analyses of river system integrity, whereby interactions between spatial patterns and ecological processes are considered, have demonstrated the importance of the context of the landscape (Hitt and Broberg, 2002) in addition to the attributes of local sites (Gergel *et al.*, 2002). Rivers are hierarchical and show distinct patterns of variability at a range of spatial scales and in response to numerous causal factors. Information regarding the landscape in which a hydrosystem is contained is essential, with the streams being linked to, and structured by the terrestrial landscape (Vondracek *et al.*, 2005). There has been a growing interest in improving our understanding of the influence of the landscape at various levels on ecosystem structures and function by identifying scales at which landscape indicators are most influential (Allan *et al.*, 1997; Molnar *et al.*, 2002). Riparian conditions and landscape uses are micro/proximal and macro/distal indicators of environmental disturbance, respectively (Pinto *et al.*, 2006). Different environmental variables of streams can be expected to vary in their sensitivity to large versus local-scale environmental factors (Allan, 2004b). Hydromorphology plays a central role over all the components acting on a river system: it especially comprises important habitat parameters for all the biota. The hydromorphological features of a river constitute a physical framework in which the biotic and abiotic interactions are organized and structured. Any change or deterioration in these conditions has a direct or indirect effect on the hydraulic conditions, and becomes an important stress factor affecting instream biota and ecological integrity. The considerable literature, dating back more than five decades, dealing with the influence of scale (Harvey, 1967; Penning-Rowsell, 1978; Carlisle *et al.*, 1989; Levin, 1992), and stream channel characteristics (Leopold and Wolman, 1957; Strahler, 1964; Hynes, 1975; Frissell *et al.*, 1986; Hawkins *et al.*, 1993) is evidence of the importance of the physical habitat as driver of ecological responses. During the last decade the increasing use of remotely sensed datasets and Geographic Information Systems, means that studies involving multiple spatial scales linked with land cover patterns have become widespread (see Orr *et al.*, 2008; Buffagni *et al.*, 2009; Kail *et al.*, 2009; Sandin, 2009; Vaughan *et al.*, 2009) .

The increasing knowledge of the interaction between various components of a river system is becoming crucial in the context of the European Union's (EU) Water Framework Directive (WFD: EC/2000/60) which requires, on the one hand, the identification of the “reference condition “of a river’s status and on the other hand, the implementation of river quality assessment tools, both for abiotic and biotic components. Traditional approaches to identify the human impact on rivers are mainly based on water chemistry and biotic indices, but these measures are the final state resulting from the initial conditions and pollution. Investigation into the changes taking place in the land cover makes it possible to detect directly the origin of unspecified disturbances. Strong relationships between land cover and nutrient concentration or export have been observed for different parameters (Johnson *et al.*, 1997; Gergel *et al.*, 2002).

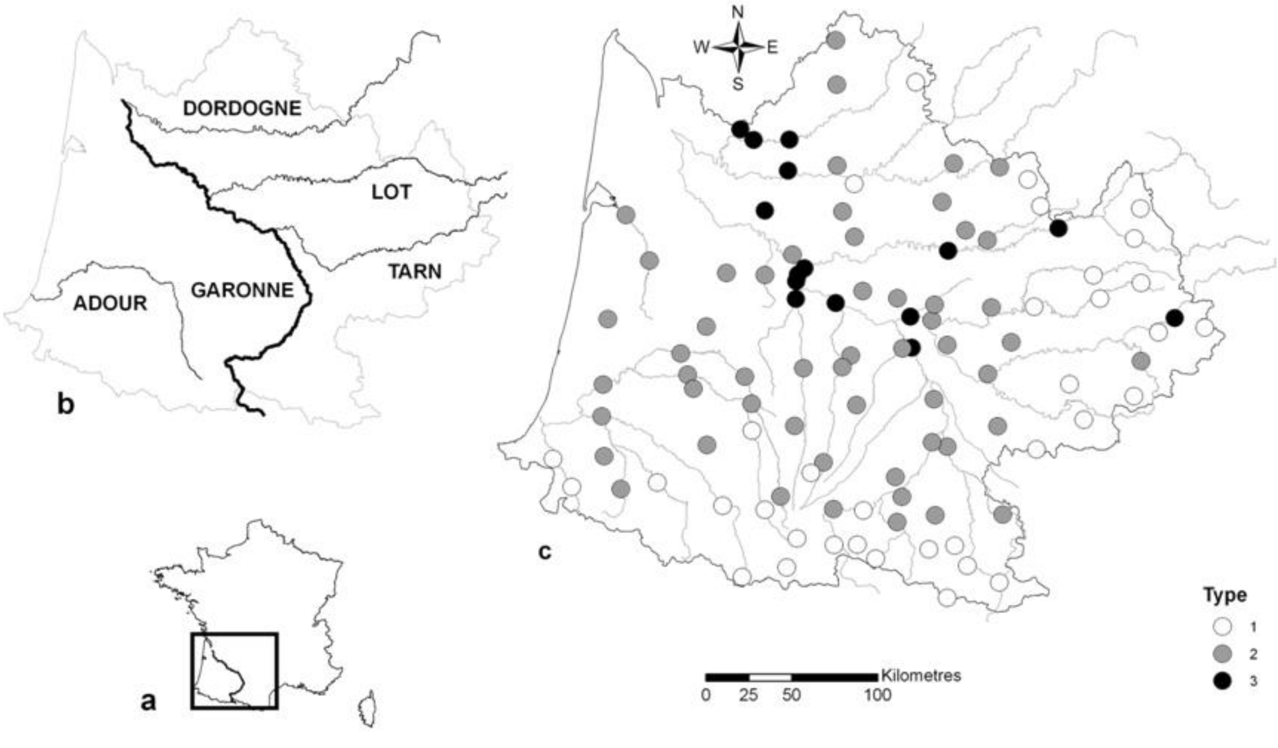
The aim of our study was to establish the links between local hydromorphological variables, such as geographical descriptors like channel and bank features or flow types at the stream reach, and the land cover patterns at multi-spatial scales. By land cover patterns we mean the ratio of the different urban, agricultural and forest classes described in Corine Land Cover 2000 (European Environment Agency, Institut Français de l'Environement - IFEN).

The study design was based on a four-stage procedure: 1) we established a typology of sampling sites from their hydromorphological features; 2) using land cover variables as predictors, we predicted the typology and determined the relevance of each spatial scale; 3) we examined the contribution of explanatory land cover variables in predicting the various hydromorphological types and 4) we established the link between hydromorphological variables independently and explanatory land cover at different spatial scale patterns in the predictive model.

2. Materials and methods

2.1. Study area

The study was conducted at 104 sites on the Adour-Garonne Basin (Figure1). The selection of sampling sites was made in order to overlap with the sampling sites of the National fish survey program in the Adour-Garonne area managed by the ONEMA (Office National de l'Eau et des Milieux Aquatiques), according to the implementation of the Water Framework Directive (WFD). The Adour-Garonne hydrographic network covers South-west France in the Atlantic area and groups together 6 main sub-basins. It extends over 116,000 km^2 from Charentes (north) and the Massif Central (east, north-east) to the Pyrenees (south), gathering 120,000 km of watercourses including 68,000 km of permanent rivers flowing into the Atlantic Ocean. The river Garonne is the main channel, running over 580 km from the central Pyrenees in Spain to the Gironde estuary on the Atlantic coast. Its major tributaries come from the Massif Central plateau (Dordogne, Lot and Tarn) and minor ones from the Pyrenean range (The Gaves); for more details about the features of the Adour-Garonne river networks see Poulain (2000) and Ecogea and Geodiga (2007). The Adour-Garonne watershed covers a wide range of altitudes (high mountains to plains and coastal areas) and geological substrates: calcareous, sedimentary, sandstone, crystalline and volcanic (Tison *et al*., 2004). From the south to the north-west, the topography and climate determine three major landscape types: the Pyrenees mountains with a pronounced relief, a vast green hilly zone of piedmont, and the valley of the Garonne River with flood zones and alluvial terraces. The oceanic influence predominates over the whole basin, but lessens to the south-east with its Mediterranean influence, dry winds and lower rainfall. The geographical features, involving climate, geology and relief are summarised in the concept of hydroecoregion. This typology of aquatic ecosystems results from the implementation of the WFD.



Figures 1. *Study area. a) location of the Adour-Garonne basin in South-western France. b) main rivers. c) location of the 104 study sites and correspondence with their hydromorphological type.*

The studied basin covers 6 hydroecoregions (Wasson *et al.*, 2001), from the south to the north: Pyrenees (headwaters of the left bank tributaries of the Garonne), Côteaux aquitains (main floodplain), and limestone Causses; to the East: Grands Causses and Massif Central (headwaters of the right bank tributaries of the Garonne) and in the west with the coastal streams of Les Landes.

2.2. Dataset of hydromorphological features

According to the terms and definitions of the European Water Framework Directive the hydromorphology is: "the physical characteristics of the shape, the boundaries and the content of a water body". This term combines two elements: 1) "Hydro" mainly described by the water velocity and flow units and 2) "Morphology" which combines local (width, bank features) and regional physical descriptors (geography, catchment structure).

The majority of the hydromorphological features of river sites were collected by field observation according to the protocol derived from the methodologies of the River Habitat Survey RHS (Environment Agency, 2003) and the "SEQ-Physique - Système d'Evaluation de la Qualité physique des eaux"- (Agence de l'eau Rhin-Meuse, 2005, 2006). The field survey sheet gives detailed information on a selection of 79 variables distributed in 9 categories. However, for pertinent statistical analyses we made a selection of 27 variables distributed in 5 categories (Table 1) as many attributes could not be registered at each site.

A 100 to 500 meter length of river channel, judged to be homogenous with regards to the substratum composition, the flow, and the surrounding environment, was chosen at each site. Each selected stretch (the length depending on the river width) was examined once during the summer with stable hydrological conditions and low turbidity. At each location, the field sheets were completed by two observers as follows: i) the data related to channel features, water velocity and river width were average values of measurements made at randomly selected locations; ii) the flow types were identified by the water surface disturbance and the flow speed according to the RHS (River Habitat Survey), the classifications of Malavoi and Souchon (2002) and Delacoste *et al*. (1995). The percentages of each flow type and plant cover of the riverbed were estimated according to the field protocol described in Hürlimann *et al*. (1999); iii) the bank erosion and the angle along the length of the reach were directly described as a percentage of the total length of both banks. The catchment hydromorphological variables were calculated using the Geographic

Information System tool with Digital Elevation Model, even though the geographical descriptors were extracted from classical cartography at 1/25,000 scale.

Categories	**Variables**	**Data type and acquisition**
Geographical descriptives	Slope	Numerical - cartography
	Altitude	Numerical - cartography
	Distance from source	Numerical - cartography
	Relief - Valley	Binary – field observation
	Relief - Plain	Binary – field observation
Channel features and flow types	Width	Numerical – field observation
	Shading	Percentage – field observation
	Water velocity	Numerical – field observation
	Chute	Percentage – field observation
	Chaotic flow	Percentage – field observation
	Rippled (riffle)	Percentage – field observation
	Laminar with disturbed surface	Percentage – field observation
	Laminar without disturbed surface	Percentage – field observation
	No perceptible flow	Percentage – field observation
Bank features	Stable cliffs	Percentage – field observation
	Eroding cliffs	Percentage – field observation
	Gentle profile	Percentage – field observation
	Steep profile	Percentage – field observation
Channel vegetation types	Filamentous algae	Percentage – field observation
	Mosses	Percentage – field observation
	Lotic hydrophytes	Percentage – field observation
	Lentic hydrophytes	Percentage – field observation
Catchment hydromorphology	Catchment area	Numerical – GIS
	Perimeter	Numerical – GIS
	Linear of watercourses	Numerical – GIS
	Drainage	Numerical – GIS
	Index of compactness	Numerical – GIS

Table 1. *Categories, names, data types and methodology of acquisition of the 27 hydromorphological variables recorded for each sampling site.*

2.3. Land cover dataset

A Geographic Information System (ESRI ArcView GIS 9.2 software) was used to determine the watershed boundaries and to extract the relative percentages of land cover (CORINE land cover 2000, Institut Français de l'Environnement - IFEN) at different spatial scales. CORINE land cover 2000 (CLC2000) is an update for the reference year 2000 of the first database which was finalized in the early 1990s as part of the European Commission program to COoRdinate INformation on the Environment (CORINE - http://www.eea.europa.eu/). The CORINE land cover database provides a pan-European inventory of biophysical land cover and constitutes a key database for integrated environmental assessment. CORINE land cover nomenclature is a hierarchical system with three levels using 5 headings for the first level, 15 for the second level and 44 for the third one (details of these categories are given in the appendix).

For the characterization of the land cover at multi-spatial scales, we used 5 patterns (commonly presented in the literature) covering 1) the whole basin (B), 2) the whole basin stream network buffer (HB), 3) a sub-basin, delimited upstream by the closer main tributary (Z), 4) the sub-basin stream network buffer (HZ) and 5) a local (L) sample reach (Table 2). For the two stream network scales (HB, HZ), the land cover was extracted with a 200 m buffer (100 m on both sides of the river), and the local sample reach (L) extended over a radius of 500 m from the sampling site. Land cover data collected at the reach scale reflected local conditions, and data collected over the entire stream upstream region (riparian corridor or entire catchment) could reflect regional conditions (Allan *et al*., 1997).

We considered both the second (CLC2) and third level (CLC3) of CORINE land cover (see appendix). Thus, the land cover extraction at 5 spatial scales combined with two levels of CORINE land cover built up 10 different databases characterising the land cover at each study site.

Code	Spatial patterns	Amplitude of scale patterns
B	Basin	Large scale
HB	Stream buffer	
Z	Sub basin	Meso scale
HZ	Stream buffer	
L	500 m	Local scale

Table 2. *Summary of the five spatial scale patterns considered. Correspondence between the codification, the spatial and the amplitude of scales.*

2.4. Modeling procedures

Our methodology encompasses analyses at multiple spatial scales, ranging from the whole basin catchment to the local scale, and including different longitudinal buffer extents. Statistical analyses, especially Random Forests (RF; Breiman, 2001a,b), have been used to determine the explanatory power of the landscape parameters at different spatial scales. A Random Forests consists of a compilation of classification or regression trees (e.g. 500 trees in a single Random Forests), and is empirically proven to be better than its individual members (Hamza and Larocque, 2005). RF models have been used with high accuracy of prediction and explanation for ecological data (see e.g. Cutler *et al*., 2007; De'ath, 2007; Peter *et al*., 2007).

Preliminary, to obtain a normal distribution, hydromorphological data were log-transformed. Then, data were standardized to reduce the variability attributed to the various range of variables and to enhance the informative signal.

Firstly, to determine the hydromorphological similarities between study sites, the 104 sites have been classified through a hierarchical cluster analysis using the Ward's linkage method with Euclidean distance measure. The Mean Split Silhouette (MSS) criterion (Pollard and van der Laan, 2002) and the Multiple Response Permutation Procedure (MRPP) (Mielke *et al*., 1976) were used to validate the clustering relevance.These steps led to a definition of the typology of the study sites called "observed type" (type) of hydromorphology.

Secondly, to predict the hydromorphology types from the different scales of land cover data, we used a newly developed machine learning technique called "Random Forests" (RF). It is a statistical classification method which has been mainly used in bio-informatics, genetics and remote sensing, and is relatively unknown in ecology (Cutler *et al*., 2007; Peters *et al*., 2007). The RF technique, introduced by Breiman (2001a,b) is an effective tool in prediction, combining tree predictors. Unlike classical regression techniques for which the relationship between input and output variables should be pre-specified, RF avoids exclusive dependence on data models. The RF is grown with a randomized subset of predictors which generate a large number of Classification And Regression Trees (CART). To model a new object from input variables, each tree of the forest produces a predictive value, and then the outputs of all the trees are aggregated to produce one final prediction. For classification, the class chosen is the one having the most "votes" over all trees, and for regression, the final value is the average value of the individual tree predictions. This technique allows the analyst to view the importance of the predictor variables. Predicted types with RF (class of prediction) were compared with observation types (class of observation) resulting from the hierarchical cluster analysis. The correct classification rate (good prediction) was obtained from the confusion matrix that identified the true or false position cases predicted, with the predictor variables being the land cover classes at multiple spatial scales. Prediction accuracy was evaluated by computing the percentage of correctly classified predictions versus observations called the prediction score or performance.

Thirdly, the relative importance of predictor variables for each model by the calculation of the mean decrease accuracy was also evaluated. When a tree is grown using a bootstrap sample from the original data, about one-third of the cases are left out of the bootstrap sample and not used in the construction; they are called oob (out-of-bag) data. This out-of-bag data is used to get a running unbiased estimate of the classification error as trees are added to the forest. The mean decrease accuracy is obtained by calculating the difference between the prediction accuracy of the oob portion and the prediction accuracy of the oob data after permuting each predictor variable. The decrease in accuracy for each predictor is averaged and standardized across all trees. This importance measure is given either for the global prediction or for each class. The relative decrease in prediction accuracy, when a predictor variable is permuted, is related to its importance in the classification (Carlisle *et al.*, 2009).

Finally, we predicted the hydromorphological variables independently with RF. The different spatial scales were tested in order to study the effect of the scale in the prediction of each variable. The accuracy of these models was tested classically using the correlation between the predicted value and the observed one.

The number of trees to grow in our RF models was set at 500 and the number of randomly selected variables to split the nodes was set at the square root of the number of predictor variables. “Leave-one-out” cross validation was applied to evaluate the generalization capacity of the Random Forests model. The data set was effectively too small to be divided into two parts and the leave-one-out procedure was therefore more appropriate (Kohavi, 1995). Moreover, this process provides a nearly unbiased estimate of the model's accuracy (Olden and Jackson, 2000).

The RF regression algorithm was implemented by the Random Forests R package (Liaw and Wiener, 2002) performed using the R environment (R Development Core Team 2004, Vienna, Austria).

3. Results

3.1. Hydromorphological based typology

From the hierarchical cluster analysis (using Ward's linkage) classifying the stations according to their hydromorphological similarities, we could divide the 104 sites into 3 main groups (Figure 2).

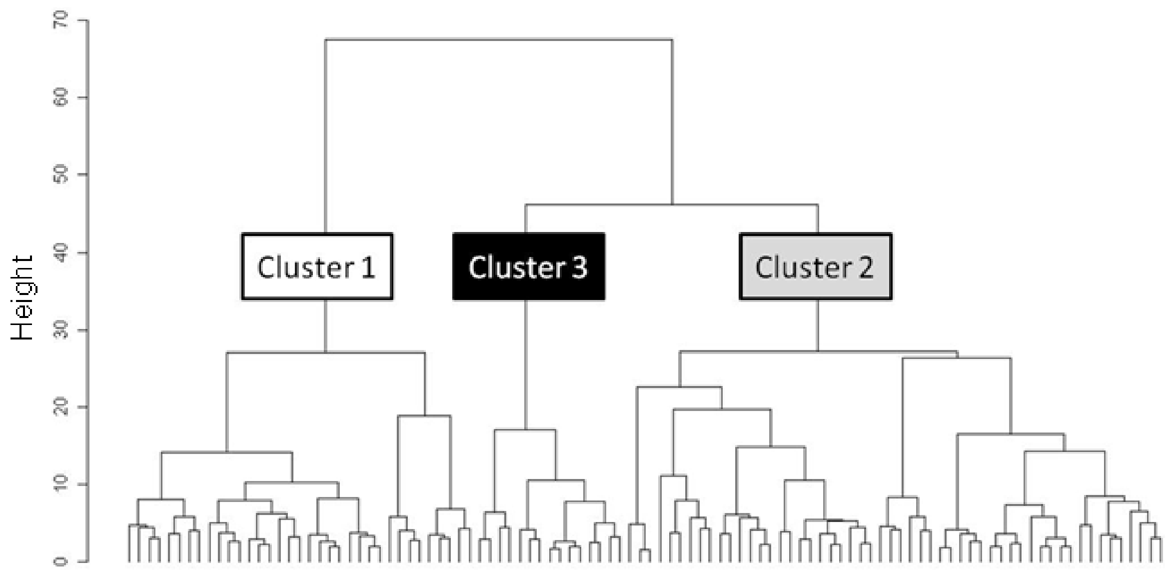
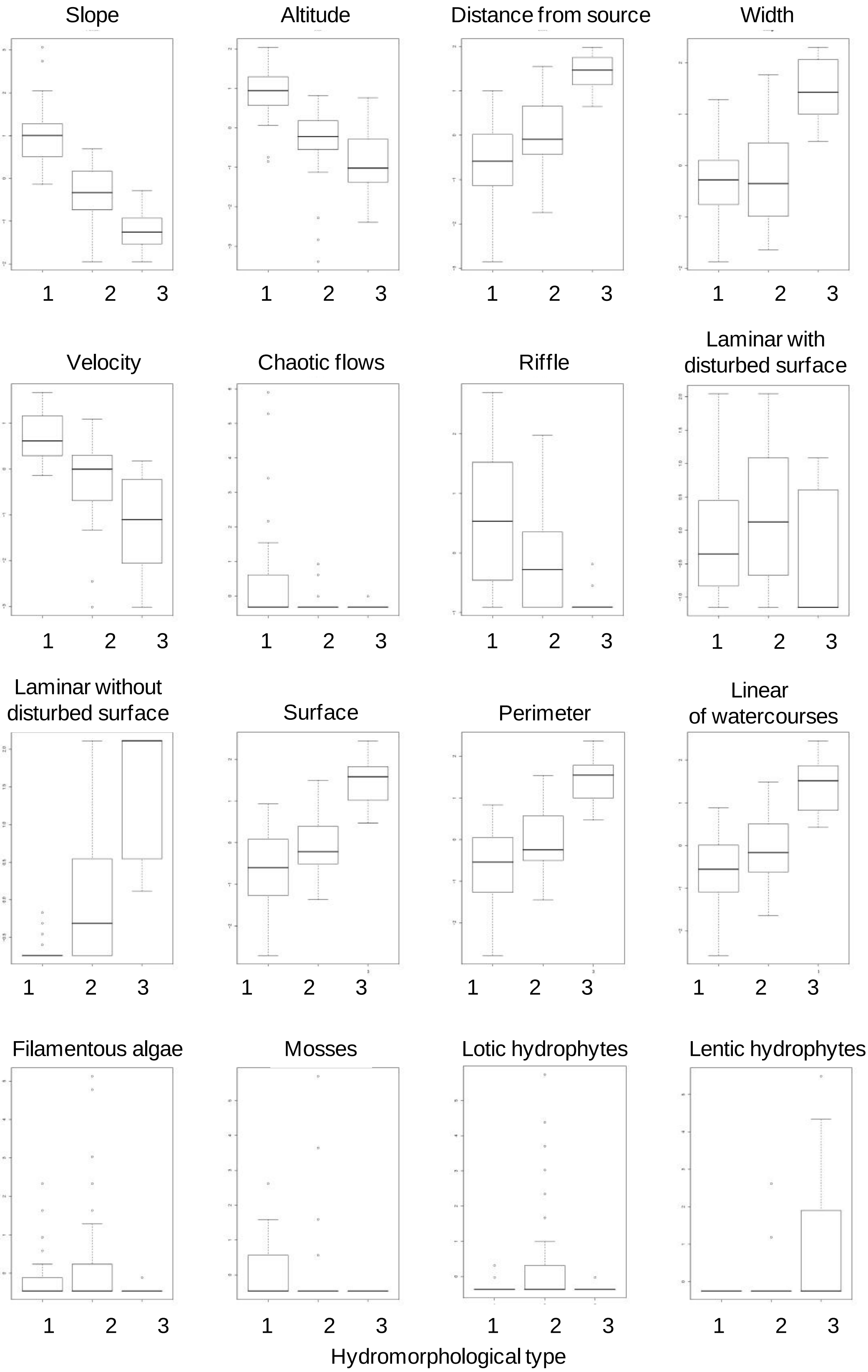


Figure 2. *Classification of the sampling sites based on the similarity of spatial hydromorphological data. Dendrogram obtained with the hierarchical cluster analysis using the Ward's linkage method with Euclidean distance measure.*

The MSS identified that the optimal level of the classification tree where the clusters were more homogenous is three. The results from the MRPP analysis showed that the differences between the clusters were significant ($p<0.001$).The sites belonging to each cluster (hydromorphology type) are presented on the map showing an apparent geographical distribution (Figure 1c).



Figures 3. *Box-plots showing the distribution of 16 main relevant hydromorphological variables in each observed hydromorphological type (1, 2 & 3). The box plots indicate the range of variable: the horizontal line in the box shows the median, the bottom and top of the box show the 25th and 75th percentiles respectively. The vertical lines represent 1.5 times the interquartile range of the data and the points represent the outliers.*

According to the spatial distribution of the clusters and their hydromorphological features summarized with the box-plot in Figure 3, we could draw up a typology of the sites as follows:

i) Hydromorphology type 1 comprised the sites at high altitude located in the Pyrenean Mountains and in the foothills of the Pyrenees and Massif Central (eastern border of the Adour-Garonne basin). These sites had the highest slope and altitude with high current velocity and turbulent morphodynamic units;

ii) Hydromorphology type 2 comes in between the two others clusters. It was composed of a majority of sites located in the Aquitaine and Garonne piedmonts and plains (western and central parts).

iii) Hydromorphology type 3, with only 15 sites, corresponded to the larger river sites mainly located in the north-western border (Dordogne basin) and in the “Nord Aquitain” plain (downstream of the river Garonne) with a large width, low velocity and smooth morphodynamic units.

In Figure 1c, three dots do not seem to match with the typology described above. These “anomalies” are two black dots (type 3) located in the eastern border of the basin, and one white dot (type 1) in the northern part. The two dots are sites in large rivers in an urban area (Tarn) or with meanders (Lot) in a large valley with slow flow. The white dot (type 1), located in lowland, is a little tributary of the river Dordogne in a wooded hilly area. Despite the fact that their geographical distribution does not fit the general observed pattern, these three sites still match with the types described above.

3.2. Prediction of hydromorphological types

The box-plots in Figure 4, illustrating the distribution of the prediction within and between the clusters for the two CORINE land cover levels, indicate that CLC3 is better in predicting hydromorphological types. On the basis of Figure 4, the focus was put on CLC3. Table 3 summarizes the scores of Random Forests and the standard deviation (SD) of the prediction score for the different spatial scales of each type. The Random Forests modeling method used to predict the typology in 3 clusters shows moderate to good predictive performance, with a scaling of prediction ranging between 40% and 87%. The model pointed out the presence of non-linear relationships between predictors and dependant variables with on average 66 % of prediction performance. The SD values show that according to each type, the spatial scale of the land cover pattern has a variable effect on the cluster performance prediction. The SD is lowest for the cluster 1 and highest for the cluster 3.

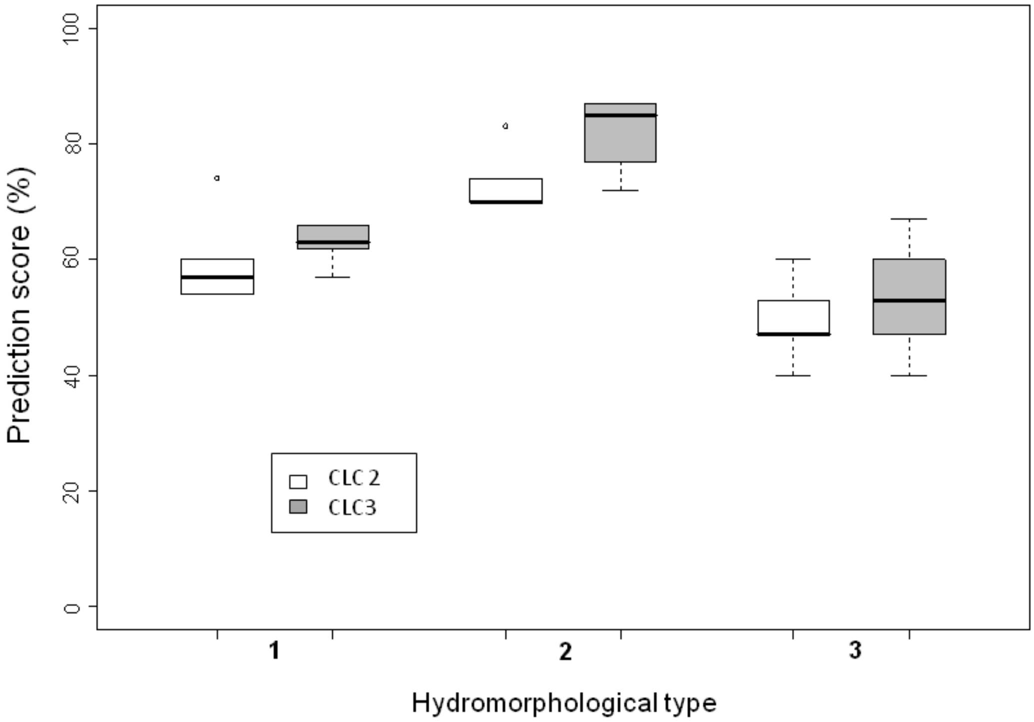


Figure 4. *Distribution of the prediction performance for each hydromorphological type for the two levels of CORINE land cover nomenclature (CLC 2 & CLC 3). The box plots indicate the range of performance among the spatial scales: the horizontal line in the box shows the median, the bottom and top of the box show the 25th and 75th percentiles respectively. The vertical lines represent 1.5 times the interquartile range of the data and the points represent the outliers.*

Land cover pattern	Type 1	Type 2	Type 3	Mean per LC pattern
CLC3_B	63	87	60	70
CLC3_HB	57	87	67	70
CLC3_Z	66	85	47	66
CLC3_HZ	62	77	40	60
CLC3_L	66	72	53	64
Mean CLC3	*63*	*82*	*53*	
Sd CLC3	*3.5*	*6.7*	*10.5*	
GLOBAL MEAN = 66				

Table 3. *Scores (in percentage) of hydromorphological type predictions based on Random Forests for the 5 spatial scales of land cover patterns for CORINE nomenclature CLC3. Mean and standard deviation (SD) per type.*

The low variability of RF scores and the low value of the SD for the type 1 mean that there is not a significant difference in predicting this type whatever the spatial scale of land cover taken into account. The local or the large spatial scales do not affect the prediction sensitivity of the hydromorphological typology of a stream reach grouping upstream mountain sites. The highest value of the SD for the type 3 results has a clear effect on the success of the prediction according to the variation in the spatial scale of land cover pattern as a predictor. The best predictions are obtained with the larger scales: the whole basin and the whole basin stream network buffer patterns. Type 2 showed intermediate SD values. The effect of the land cover scale variation is more moderate than in type 3 but clearer than in type 1. A local scale seems to be the less relevant pattern whereas a large scale gives more accurate predictions.

3.3. Contribution of explanatory land cover variables in predicting hydromorphological types

The relative importance of variables derived from Random Forests highlights the contribution of land cover predictors in the hydromorphological type prediction. The results are presented in Figure 5 for the 3 hydromorphological types. According to the previous results, the relative importance was averaged for each variable using a selection of the more relevant land cover scale patterns assigned to each type: for type 1 the five scale patterns were averaged, patterns B, HB, Z & HZ for type 2 and B & HB for type 3. As shown in Figure 5, “non-irrigated arable land”, “water courses” and “natural grasslands” are the three main land cover classes explaining 35 % of type 1. Only 2 classes of land cover are above 10 % of contribution to explain type 2, “natural grasslands” common with type 1 and “coniferous forest”. In type 3, the maximum contribution of the explanatory variables is less than 10 %. The three most important land cover classes are the “fruit tree plantation”, “water courses” and “artificial surfaces”. The “water courses” class is the only one showing a similar importance in the 3 types. The high homogeneity for both net river and drainage density throughout the Adour-Garonne basin accounts for the similar importance of the land cover class “water courses” in the 3 types. Besides, the variables “drainage” and “linear of watercourses” were not considered as pertinent, owing to their invariance, when classifying the sites into three types.

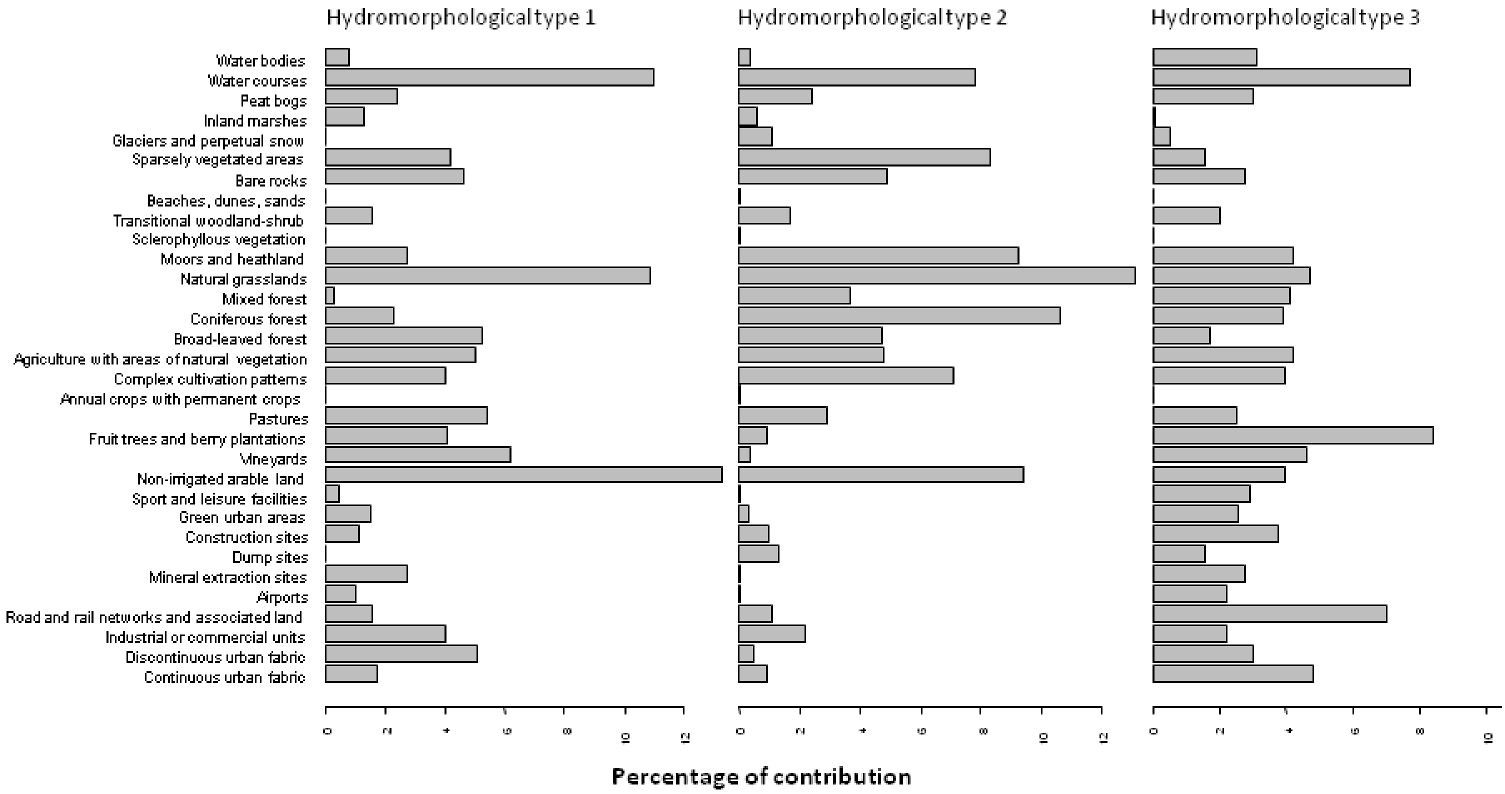


Figure 5. *Relative contribution (%) of explanatory variables for the 3 hydromorphological types. The most relevant scale patterns of land cover are averaged for each type.*

In order to point out the importance of the land cover classes in the prediction of hydromorphological type, we draw a parallel between what it is observed on the field (land cover) at the most commonly spatial scale used (whole basin) and their theoretical contribution to explain the hydromorphological types (RF results). To do that, and to facilitate and make the analysis more relevant, we grouped the classes of land cover into only 4 major classes: artificial surfaces, agricultural areas, forests & natural areas and wetlands/ water bodies (similar to label level 1 of CORINE Land cover). The results presented in Table 4 point to the dominance of forest cover upstream (type 1) whereas agricultural areas become dominant downstream (types 2 and 3). Although the percentage of artificial areas remained under 2%, there was an obvious increase in this class from type 1 to 3. The most significant element emerging from this analysis is the large shift between the representation of the land cover in the basins and the percentage of contribution in the prediction of the types. This fact is particularly important with respect to the class “Artificial areas” which, whatever the considered types, represented less than 2% of surface whereas its contribution ranged from 7.5% to 33%. This is also the case for the “water bodies” with very low surface areas (<0.5%

of the areas) which represented 10 to 14% of the contribution. In the case of the "Agricultural areas", the contribution was maximal in type 1, and for the class "Forest", the highest contribution was in type 2.

	Hydromorphological					
	Type 1		Type 2		Type 3	
	% land cover	% contribution	% land cover	% contribution	% land cover	% contribution
Artificial areas	1.1	18.0	1.5	7.4	1.8	33.0
Agricultural areas	34.1	37.0	55.2	25.4	56.0	27.6
Forest	64.5	30.0	43.2	57.0	41.9	25.5
Wetlands/water bodies	0.3	15.0	0.2	10.2	0.4	13.9

Table 4. *Percentage of land cover classes versus percentage of contribution for each hydromorphological type. The land cover classes have been gathered into the 4 main categories based on CLC1 nomenclature (the classes wetlands and water bodies are gathered).*

3.4. Performance measures to predict hydromorphological variables from different explanatory land cover patterns

In order to investigate any relationships between the hydromorphological variables and multi-spatial scale of land cover patterns, we used the performance measures between the observed hydromorphology and the predicted values (Table 5). Only 17 variables were considered because the correlation between land cover and some hydromorphological variables (such as geographic description or catchment hydromorphology) is nonsense. The results show the ability of the models using the larger scales of land cover pattern to predict hydromorphological data, as 9 variables have performances superior to 0.30. At the local scale, only two variables have high correlation coefficients. The highest correlation coefficients were observed for "width" and "water velocity" and can be quite well predicted from all scales of land cover patterns.

	Land cover patterns				
Hydromorphological variables	CLC3B	CLC3HB	CLC3Z	CLC3HZ	CLC3L
Width	0.87	0.87	0.73	0.75	0.66
Water velocity	0.45	0.58	0.45	0.44	0.31
Chaotic flow	0.29	0.44	0.31	0.28	-0.01
Cascade	0.33	0.34	0.13	0.17	0.21
Riffle	0.32	0.21	0.34	0.35	0.29
Smooth surface with current	0.41	0.41	0.22	0.22	0.10
Smooth surface without current	0.42	0.48	0.36	0.35	0.26
Lentic chenal	0.04	0.02	-0.04	-0.01	-0.07
Stable bank	0.03	-0.10	-0.03	-0.06	-0.04
Unstable bank	0.03	-0.12	-0.04	-0.05	-0.04
Gentle bank profil	0.38	0.38	0.31	0.29	0.13
Steep bank profil	0.38	0.35	0.29	0.27	0.16
Filamentous algae	0.07	0.04	0.00	0.01	0.01
Bryophytes	0.45	0.37	0.20	0.22	0.07
Lotic hydrophythes	0.12	0.13	-0.05	-0.06	-0.11
Lentic hydrophytes	0.26	0.25	0.30	0.25	0.12
Helophytes	-0.14	-0.10	0.00	0.00	-0.06

Table 5. *Performance measures of the hydromorphological variables predictive model using different land cover patterns classes as predictors (CLC3B, CLC3HB, CLC3Z, CLC3HZ and CLC3L): correlation coefficient between measured hydromorphological variables and the values predicted using different land cover patterns. Grey scale indicates values greater than 0.5 and 0.3.*

4. Discussion

4.1. Hydromorphological based typology

Similarly to other hydromorphological studies in Central Europe (Sandin and Verdonschot, 2006), the first environmental variability that we obtained was along a mountain/lowland gradient where large-scale factors are predominant (first dichotomy in the dendrogram between cluster 1 and clusters 2-3). The second partition between clusters 2 and 3 defines a gradient of “mid-size lowland streams” to “large size rivers” on the stream-bottom slow-flowing without a distinct valley. In the background of these results, the channel vegetation type plays a secondary role in the definition of the typology classification and represents distinctive components of each type. Types 1 to 3 are represented respectively by i) mosses, ii) filamentous algae and lotic hydrophytes, and iii) lentic hydrophytes. Local variables such as bank structure or other variables of catchment hydromorphology (drainage, index of compactness) seem to have a smaller effect in defining the typology. These results underline the hierarchical overlapping of hydromorphological variables, where geographical features (slope, altitude, distance from source, width) and catchment hydromorphology parameters (perimeter, catchment area) emerge as key factors in modeling hydromorphological typology. These factors concerning a large area reveal the use of large scale variables to analyze the typological aspect (Feld, 2004).

4.2. Prediction of hydromorphological types

The prediction of hydromorphological types with the RF highlights three significant outcomes in terms of the relevance of the predictions according to i) the nomenclature level of CORINE land cover, ii) the type and, iii) the scale of land cover pattern. Thus, firstly, the reduction in the number of predictors (CORINE land cover classes) seems to be unfavorable for prediction with Random Forests, whereas the CORINE nomenclature level 3 (CLC3) proved to be more suitable. As described in Goldstein *et al.* (2007), "more refined classifications of land cover would probably improve attempts to relate land use to stream ecosystems". Secondly, the Random Forests prediction scores are clearly influenced by the number of sites in each type. Type 2 (54 sites) which gave the best performance measures gathered the majority of the study sites whereas type 3 (15 sites) which has the lowest number of study sites had the lowest score, Type 1 (35 sites) comes in between the two other groups. Moreover, it is established that the relations between the hydromorphological typology of a stream reach and the consideration of different spatial scale of land cover react to a longitudinal upstream/downstream gradient. In the head watercourse mountain sites (type 1), the land cover patterns have the same effect on the hydromorphological features whatever the spatial scale considered: no significant differences are identified. Downstream, in the flood plain (type 2), some perceptible differences appear, in particular local CORINE land cover has less influence. At the other end of the gradient, large scales are predominant and are strongly correlated to the settings of the hydromorphology.

In the literature the results are frequently contradictory and the role of near-stream vs. larger spatial scales can be difficult to separate (Allan, 2004a). While some studies concluded that there are stronger relations with large spatial scales (Roth *et al*., 1996), and others, on the contrary promote closer relationships with smaller scales (Lammert and Allan, 1999; Allan

2004b), Vondracek *et al*. (2005) and Kail *et al.* (2009) reported that both local and catchment scale are significantly related to hydromorphology. Lammert and Allan (1999) suggested that these different outcomes might be explained by differences in study design."

While the results showed that the scale of land cover information influences the prediction of hydromorphological types (large scale to local scale), the type of spatial pattern (basin *vs* buffer) showed no clear effect on prediction power.

4.3. Contribution of explanatory land cover variables in predicting hydromorphological types

The analysis of the contribution of explanatory land cover variables for hydromorphological type prediction shows that despite their equal richness for the three types (32 land cover classes), the distribution of the importance of the land cover class patterns appears to be characteristic for each of them. This feature denotes a specific land cover effect on each type. These results underline an upstream/downstream gradient with a gradual decrease in the contribution of the explanatory variables. Upstream, in type 1, only a few land cover classes have a high degree of contribution. Thus, on the one hand in the headwater, the hydromorphological typology of the sites seems to be closely linked with well defined and specific land cover classes. On the other hand, the relative contribution of land cover classes tends to be progressively less indicative and more homogenous in cluster 2 and even more so in cluster 3. Downstream, in the flood plain, the link between the hydromorphological typology and the land cover classes appears to be a "non-specific" relationship. In addition, the parallel drawn between the percentage of land cover and the percentage of contribution indicates that whatever the hydromorphological type, the dominant class of land cover is not the most contributive in predicting the hydromorphological type. We can interpret this effect as follows: the main hydromorphological types are described by a homogeneous frame, built with a set of major and structuring classes. On the other hand, the minor land cover classes appear to be the more sensitive. These marginal classes react like pertinent sensors to detect changes taking place in the different hydromorphological units.

4.4. Performance measures to predict hydromorphological variables from different explanatory land cover patterns

The correlation between the observed values and the predicted hydromorphological variables with the land cover pattern was highest with the two larger scale patterns of land cover (whole basin and stream whole basin network buffer). The local and median extents (sub-catchment and stream sub-basin network buffer - meso scale) appear to be irrelevant. Secondly, the correlations established with the physical data ("width" and "water velocity") are quite good: the highest correlation is with the "width". In the context of these results, we underline the decrease of the correlation coefficient from the large scale to local pattern that highlights the sensitivity and the accuracy of the analysis. Except for the "lentic canal" variable, all the morphodynamic units are rather well linked with the large scale of land cover patterns. Concerning the "bank structure" attributes, only the data about the bank profile gives good correlations; stability of bank being less related whatever the land cover scale pattern. It is known that the stability of banks is strongly dependent on surrounding conditions; therefore this expected point is not recorded. This results from the study design where mainly natural and non-physically modified river reaches have been sampled. On the contrary, the variable "profile" is registered more clearly and appears to be a reliable parameter to large scale patterns of land cover. The aquatic vegetation performs poorly: only "mosses" and "lentic hydrophytes" correlated with the land cover. The variable "aquatic vegetation" is not directly a variable of hydromorphology but it is closely related. The results concerning the aquatic vegetation are in accordance with those obtained with respect to the physical variables and the morphological descriptors. The mosses are indicative of running water in a cascade or riffle, although helophytes are adapted to more lentic areas, for which correlation is less strong. Thus we found biological components and physical features indirectly correlated.

5. Conclusion

Rivers have their own internal structure composed of a variety of hydrodynamic units, making them internally heterogeneous landscapes (Wiens, 2002). The structural and functional internal architecture that characterizes a hydrosystem is integrated, and reflects a broader terrestrial environmental context; the challenge then is to define the relevant limits of this influence (Vaughan *et al*., 2009). From this perspective, the goal of the present study was not to establish the connection between each single land cover class with each specific hydromorphological variable by setting out cause-effect relationships (one-to-one relation), but to globally consider the closest link between a set of local hydromorphological descriptors and the variation of spatial scale of land cover.

Based on hydromorphological features, the classification of the 104 sites distributed all over the Adour-Garonne basin made it possible to define a typology. This typology clearly shows an upstream/downstream gradient where the geographic descriptors (large scale factors) are the structuring elements. This expected result needs to be compared with the predictive typologies produced by Random Forests with the different scales of land cover patterns. Attempts to identify the spatial scale of the land cover which correlated best with the hydromorphological reach features indicated that catchment-wide land use (whole basin or stream buffer) seems to be the most significant, in agreement with Allan *et al*. (1997). Land use predictors diminished to insignificance as the spatial scale decreased. Whatever the distribution of stream reaches in the headwater or in the floodplain, large scale land use was shown to be a strong predictor of hydromorphological settings. Somewhat surprising was the finding that the local scale was not the most significant or the indisputable predictor unit even though intuitively stream reach physical characteristics would be expected to be under the direct influence of adjacent land use. Concurrently, the explanatory land cover variables showed the same gradient with a gradual decrease in their contribution. Upstream, the contributions of the land cover class were well established, and progressively they become homogenous.

The prediction performance, established between hydromophological features and land cover pattern, showed a better relationship with the larger scale. Nevertheless, discrepancy between the different spatial scales remained weak. The results led to a trend showing that the catchment scale seems to be of primary importance. Smaller scales appeared to be in the background but in any case are of importance. These findings, putting in the foreground the larger scale, must be considered in a restricted framework where the selected studied sites are not affected by any physical impairment and the land cover resolution is based on CORINE Land Cover GIS processing. In a context of natural condition the results appear to be useful for examining the origins of the connection between land use and the local river hydromorphological dynamics. In particular, it is demonstrated that a zooming in on land use does not provide a better or more relevant connection with the components of the habitat of a local river reach. The land cover database is necessary for the analysis of the causes and consequences of natural and artificial processes, impact assessment, identification of trends and the contribution to the maintenance of the ecological balance and its consideration in decision-making processes. Nevertheless much attention must be given on land cover resolution. Our study design dealt with spatial scale but did not take into account change in land cover resolution. A further investigation would be to modify land cover resolution in parallel with the spatial scale, in other words: CORINE Land Cover resolution for catchment scale and a thinner field observation resolution for local scale (i.e. presence of narrow-vegetated buffer strips not detected by CORINE Land Cover). While few studies have focused on the relationships between hydromorphology and land cover at multi-spatial scales, our investigation carried out in South Western France could have useful applications for local policies and for agents in charge of the surveillance program of the aquatic environment. Understanding how land cover structure at multiple spatial scales is linked to hydromorphological features could facilitate the development of effective conservation strategies and tools. This paper fits particularly well with the implementation of the European Water Framework Directive that requires long-term sustainable management based on a high level of protection of the aquatic environment and the prevention of its deterioration. Hydromorphology assessment forms an integral part of the WFD survey and monitoring program. The typology required by the WFD is mainly aimed at the definition of specific condition references. In France, the national WFD river typology approach is based on the Hydroecoregion (Wasson *et al.*, 2002) delimited by geology, relief and climate features. Within these homogenous geographical entities, streams and rivers exhibit common characteristics. A clear distinction between natural variability and human impact is necessary (Verdonschot and Nijboer, 2004). In the specific context of natural conditions exempt of notable physical impairment our study provides underpinning outcomes. As key findings in the frame of the assessment of natural conditions, we advise that the larger extent, i.e. the catchment scale, should be given high priority when connected with a set of land cover/uses. If the larger condition appears to be a greater value for natural conditions; local and riparian environment could supply valuable information in the case of impacted sites. Divergence between the strength of the relationships Hydromorphology /Land Cover at the catchment scale and Hydromorphology /Land Cover at local scale could be interpreted as a sensor of hydromorphological impairment.

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CHAPITRE 3

Relationships between multi-scale land cover patterns, water physico-chemistry and diatom-based metrics in the rivers of the Adour-Garonne basin (southwestern France)

[In preparation] | Water Research

Relations entre l’occupation des sols à diverses échelles spatiales et des métriques de physico-chimie des eaux et de diatomées dans les rivières du bassin Adour-Garonne (S.O., France)

Résumé

L’échelle-dépendance des phénomènes écologiques demeure une problématique centrale en écologie, particulièrement dans les milieux aquatiques. La considération de l’échelle spatiale appropriée pour évaluer les effets du paysage sur les conditions écologiques des cours d’eau est une phase critique. Comprendre à quelle(s) échelle(s) le paysage environnant et les perturbations humaines affectent la qualité des eaux à un point donné du réseau hydrographique est donc essentiel pour mettre au point des stratégies adaptées de protection et de réhabilitation des écosystèmes d’eau douce. Les recherches axées sur les réponses biologiques face aux perturbations du milieu ont généralement été conduites à une seule échelle. De plus, les résultats de ces études se sont souvent montrés divergents mettant en avant soit la prépondérance des échelles les plus larges soit la prédominance des échelles locales. D’autre part, la majorité des études traitant des échelles spatiales ont examiné les relations entre les métriques du paysage et un seul composant clé des écosystèmes.

Dans ce cadre, nous présentons les résultats d’une étude évaluant l’influence de l’occupation des sols (O.S.) à différentes échelles spatiales extraites de traitements SIG sur des métriques de qualité de l’eau. La métrique « qualité des eaux » rassemble les relevés physico-chimiques de treize paramètres ainsi que des données relatives aux diatomées benthiques (huit indices diatomiques). L’étude a été conduite dans cinquante-trois sites répartis dans le bassin Adour-Garonne caractérisé par un large panel de conditions chimiques et biologiques. L’analyse statistique des bases de données s’est faite par la méthode STATIS. Cet algorithme est une extension de l’analyse de co-inertie permettant le traitement de plusieurs bases de données ayant au moins une dimension en commun.

L’objectif principal consistait alors à déterminer quelles échelles spatiales expliquent le mieux la physico-chimie des eaux et les métriques de diatomées benthiques. La réponse à cette question s’est faite par la résolution d’étapes intermédiaires qui consistaient à i) évaluer « l’effet cascade » depuis le paysage jusqu’aux diatomées *via* la chimie, ii) établir l’échelle

dépendance entre l'O.S., la physico-chimie et les diatomées à partir de la force des relations entre ces métriques prises deux à deux ; et iii) estimer la pertinence du grain de l'O.S.

Les résultats ont montré une hiérarchie croissante de la force des liens entre métriques, de l'occupation des sols à la physico-chimie et aux diatomées, soulignant la continuité des processus écologiques le long du gradient et leurs impacts cumulatifs intégrés dans « l'effet cascade ». La force des liens entre métriques est plus élevée dans le cas de relations directes (O.S./chimie, chimie/diatomées) que dans le cas de la relation indirecte entre O.S. et diatomées. Il est confirmé que la réponse des diatomées face aux patrons d'occupation des sols est indirecte et se fait *via* la physico-chimie. Il ressort également que les relations entre métriques s'établissent avec le plus de force lorsque l'échelle spatiale est la plus vaste, c'est-à-dire, dans notre cas d'étude, la totalité du bassin versant. Les résultats confortent ainsi l'idée que les patrons d'occupation des sols à l'échelle du bassin ont plus d'influence sur la qualité des eaux que les conditions locales ou intermédiaires du paysage. De plus il apparait que le grain intermédiaire de Corine land cover est le mieux adapté aux caractéristiques du bassin Adour-Garonne.

Tous ces résultats apportent des informations pertinentes aux question-clés concernant les programmes de monitoring basés sur les diatomées dans le contexte de la mise en œuvre de la Directive Cadre Européenne. Dans le cadre de l'évolution des méthodes de bio-indication, la prise en compte des perturbations potentielles du paysage définies à partir des métriques d'occupation des sols à l'échelle du bassin versant constituera nécessairement une prochaine étape.

Relationships between multi-scale land cover patterns, water physico-chemistry and diatom-based metrics in the rivers of the Adour-Garonne basin (southwestern France)

Loïc Tudesque, Clément Tisseuil and Sovan Lek

Abstract

The scale dependence of ecological phenomena remains a central issue in ecology. Particularly in aquatic ecology, the consideration of the accurate spatial scale in assessing the effects of landscape factors on stream condition is critical. In that context, we present the results of a study assessing the influence of multi-spatial scale land cover patterns extracted from GIS process on water quality metrics measured at stream reach. The investigation was conducted at 53 sites spread over the Adour-Garonne basin characterized by a large range of physico-chemical and biological conditions. The water quality metric pools physico-chemical data (thirteen parameters) and benthic diatom metrics (height diatom indices). To assess the strength of the relationships between the water quality and the land cover at multi-scale, the modeling procedure has been based on the STATIS approach.

Our findings have shown that the increased strength of the relationships between metrics, from land cover to water physico-chemistry to diatoms, emphasizes the continuity of processes along the gradient and their cumulative impacts integrated into a "cascade effect". It is confirmed that the diatom metrics respond to land cover patterns through water physico-chemistry by indirect pathways across the largest spatial extent (i.e., the whole catchment area). The overall results reinforced assertions that the land cover patterns at the catchment spatial extent are more influential on water quality than the local or intermediate landscape conditions. In addition, the intermediate grain of Corine land cover (i.e., sub-classes) appears to be the most appropriate in our case study. All these findings provide relevant information to key-question concerning diatom-based monitoring programs in the context of the Water Framework Directive implementation. We concluded that in the scope for the improvement of biomonitoring methodologies, taking into account the potential landscape disturbance toward land cover pattern metric at the catchment scale might be a next promising approach.

Keywords: diatom metrics; land cover; spatial scale; STATIS; water quality

1. Introduction

Understanding how ecological processes are interconnected over multiple spatial scales from local community structure to global patterns is of paramount importance for the research in ecology (Levin 1992, Thompson et al. 2001). In freshwater ecology, gaining insight on how factors interconnect and operate across different scales (Vondracek et al. 2005, Brazner et al. 2007) and understanding at which scale the surrounding landscape and human disturbances are affecting water quality at a given point are essential (Gove et al. 2001) to adapt scale-appropriate strategies for protecting and rehabilitating stream ecosystems.

Although there are exceptions (e.g., Roth et al. 1996, Strayer et al. 2003, Pan et al. 2004), the investigations carried out on biological responses facing disturbances have generally been conducted at a single spatial scale. Results from these studies are usually not consensual, highlighting the predominant influence of local (e.g., Sponseller et al. 2001, Meador and Goldstein 2003, Kail et al. 2009) or large (e.g., Potapova and Charles 2002, Park et al. 2006) spatial scale landscape factors on aquatic ecosystems.

The majority of studies dealing with spatial scale have mainly examined the relationships between landscape metrics and one key component of freshwater ecosystems, e.g., hydromorphological features (Orr et al. 2008, Buffagni et al. 2009), water physico-chemistry (Dodds and Oakes 2006, Boeder and Chang 2008) or biota (Hopkins II and Burr 2009, He et al. 2010). A few studies have gathered the relationships between several key-components of hydrosystem at multi-spatial scale whereas there is a recognition that aquatic ecosystems are hierarchically organized in space. However, identifying the appropriate scales at which both biota and physico-chemistry best respond to land cover patterns is highly promoted by the European Water Framework Directive (WFD; 2000/60/EC European Parliament and Council 2000). In order to maintain and restore the “good ecological status” of rivers by 2015, as required by the European Directive, the implementation of relevant river quality assessment and management tools needs to include accurate consideration of spatial scale.

In that perspective, the originality of our research is to gather data from land cover at multi-spatial scales, water physico-chemistry and benthic diatoms sampled at stream reach in a common analytical process. The overall objective is to determine which spatial scale of land cover is likely to best explain the water physico-chemistry and the diatom metrics (diatom indices) in a major European river system, the Adour-Garonne basin (SW France). For this basic purpose, the study design has been based on three intermediate stages which are to: 1) assess the “cascade effect” from landscape factors to diatom metrics through water physico-chemistry; 2) establish the spatial scale dependence between land cover, water physico-chemistry and diatom metrics through the strength of the pairwise relationships established at different spatial extents; and 3) estimate the relevancy of land cover grain.

Finally we have established the relevancy of our results and have projected our findings in the perspective of the improvement of the diatom-based monitoring tool in the context of the WFD implementation.

2. Material and methods

2.1. Study area

The Adour-Garonne hydrographic network covers South-west France in the Atlantic area and comprises six main sub-basins. The network extends over 116,000 km2 from Charentes (north) and the Massif Central (east, north-east) to the Pyrenees (south), gathering 120,000 km of watercourses including 68,000 km of permanent rivers flowing into the Atlantic Ocean. The river Garonne is the main channel, running over 580 km from the central Pyrenees, in Spain, to the Gironde estuary on the Atlantic coast. For more details about the features of the Adour Garonne river networks see the reports of Poulain (2000) and Ecogea & Geodiga (2007) or Park et al. (2006).

The investigation was conducted at 53 sites spread over the Adour-Garonne basin, characterized by a large range of physicochemical and biological conditions (Figure 1). The selection of sites was made in regards to the geographical and temporal overlap between benthic diatom inventories and water chemistry data.

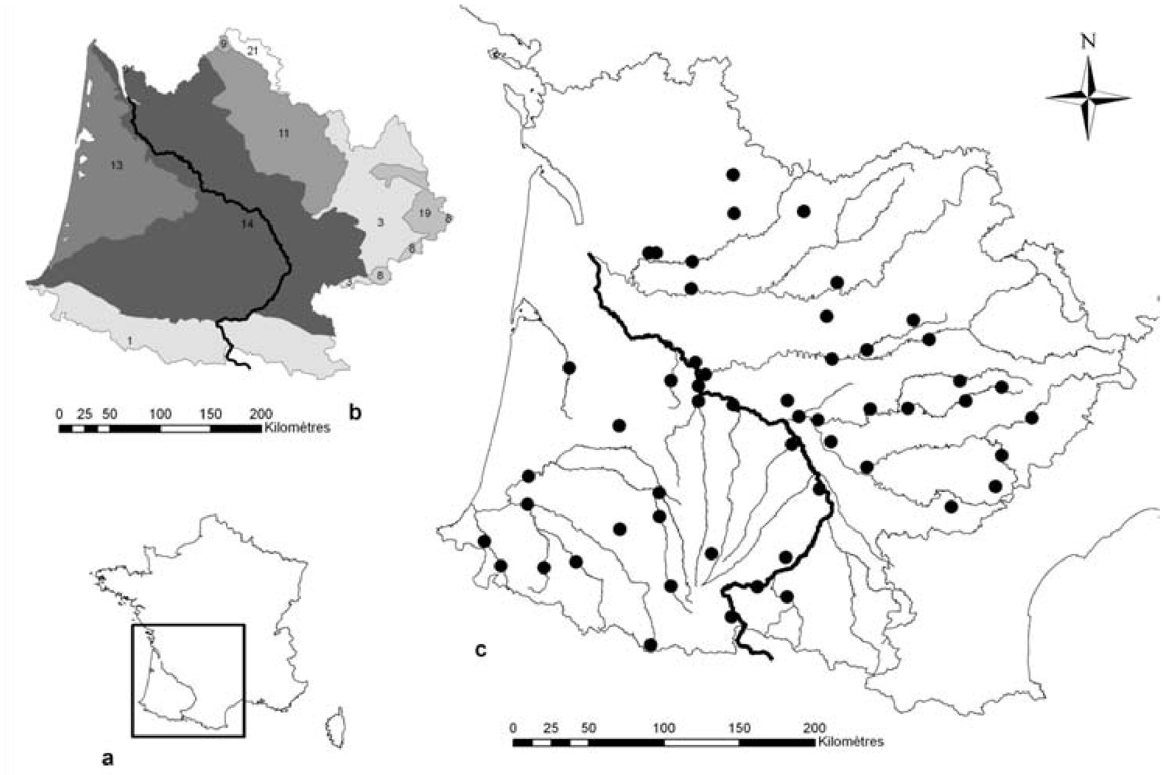

Figure 1. *a) Location of the study area in South western France. Garonne river in bold ; b) 10 hydro-ecoregions within the Adour-Garonne basin; c) locations of sampling sites with the main river network.*

2.2. Data collection

The design of our approach has been oriented around spatial relationships during the summer base-flow period to eliminate variations of material fluxes caused by flow variation and sampled mature periphyton communities. Summer low-flow period is the most useful period in assessing stream water quality, this period offering important limiting and restricting conditions for aquatic biota (i.e., concentration of various pollutants).

2.2.1. Physico-chemistry

Physico-chemical data came from the Adour-Garonne Water Agency database supplied in the framework of the regional routine monitoring program. Thirteen major physico-chemical variables were selected. These variables included conductivity (Cond), suspended matter (SM), pH, water temperature (Temp), as well as some variables related to the eutrophication (NH_4^+, NO_3^-, NO_2^-, PO_4^{2-}, total Phosphorus - Pt) and saprobity (biological oxygen demand - DBO5-, dissolved oxygen – O_2, oxygen saturation - Sat, organic carbon - CO).

2.2.2. Land Cover

We used a Geographic Information System (Arc View 9.2, ESRI) to extract the relative surface area from the CORINE land cover 2000 database (European Environment Agency 2005) at different spatial scales (grains and extents), as summarized hereafter and fully described in Table 1 and appendix.

The land cover spatial grain reflects the hierarchical structure of Corine land cover nomenclature, embedded within three levels of increasing resolution details: (1) five headings for the first level (CLC1); (2), 15 headings for the second level (CLC2) and (3), 44 for the third level (CLC3).

The land cover spatial extent includes five nested spatial units commonly used in the literature, ranging from the whole basin upstream the sampling site to local area : 1) the whole basin (B); 2) the whole basin stream network corridor (HB); 3) a sub-basin, delimited upstream by the closest main tributary (Z); 4) the sub-basin stream network corridor (HZ) and; 5) a local (L) sample reach (table 1 and figure 2). For the two scales of stream network corridor (HB, HZ), the land cover was extracted with a 200 m buffer (100 m on both sides of the river), and the local sample reach (L) extended over a radius of 500m from the sampling site. Overall, 15 different land cover spatial scales were considered, combining the three spatial grains and five spatial extents (figure 3).

	Code	Spatial extent	Spatial grain
15 spatial scales (extent + grain)	B1	Basin	1
	B2		2
	B3		3
	HB1	Basin stream corridor	1
	HB2		2
	HB3		3
	Z1	Sub-basin	1
	Z2		2
	Z3		3
	HZ1	Sub-basin stream corridor	1
	HZ2		2
	HZ3		3
	L1	500 m	1
	L2		2
	L3		3

Table 1. *Summary of the fifteen spatial scale patterns (extent + grain). Correspondence between the codification, the spatial and the amplitude of scales.*

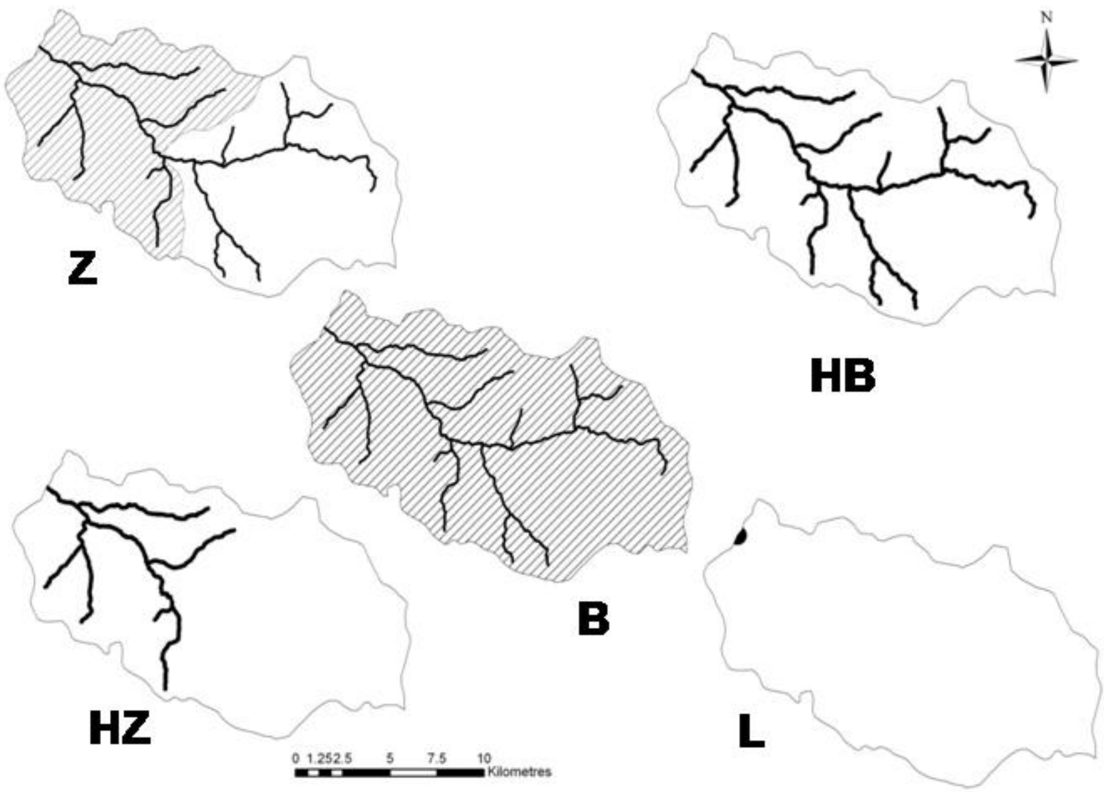

Figure 2. *Example of a random studied outflow reach showing the 5 spatial extent patterns used to extract the land cover. B = whole basin (hached area); HB = whole basin stream network buffer; Z = sub-basin (hached area); HZ = stream sub-basin network buffer; L = local sample reach.*

2.2.3. Benthic diatoms dataset

The benthic diatoms were sampled from hard substrates (cobbles) in riffle or running sections which were free from sediment and filamentous algae using standard procedures (AFNOR 2000, CEN 2002). The identification of the diatom flora was done at the specific or infra-specific level according to the major European diatom flora handbooks (i.e., Krammer and Lange-Bertalot 1991-1997, Lange-Bertalot 2001).

The diatom database has been managed with the software OMNIDIA (http://omnidia.free.fr/omnidia_english.htm). This software is both a useful tool for the management of the inventories, the rapid calculation of various diatom indices and represents a powerful taxonomical and ecological database (Lecointe et al. 1993, Poulin et al. 2001). Frequently updated since its creation in 1982 by the Cemagref, it is commonly used in France in the framework of biomonitoring and bioassessement by researchers or agent in charge of the water quality survey in the Water Board.

We synthesized the ecological features of diatom assemblages using two types of index. The first category corresponds to global water quality indices represented by the Specific Polluosensitivity Index (SPI; Coste in Cemagref 1982) and the Biological Diatom Index (IBD; Lenoir and Coste 1996; AFNOR 2000). These indices are commonly used in France and integrate different physico-chemical characteristics of waters (Prygiel et al. 1999): pH, conductivity, organic matter load, phosphorus and nitrogen). The second category of indices correspond to six specialized indices reflecting specific ecological spectrum of diatom communities according to van Dam et al. (1994): salinity (IndSal), oxygen requirements (IndOxy), pH (IndpH), saprobity (IndSap), trophic state (IndTro) and nitrogen uptake metabolism (IndAuto). The calculation is based on the weighted average equation from Zelinka and Marvan (1961):

$$\mathrm{ID} = \frac{\sum_{j=1}^{n} A_j I_j V_j}{\sum_{j=1}^{n} A_j V_j}$$

Where *A* is the relative abundance of the species *j*, *I* the sensitivity value of the species *j* for a given parameter (e.g., pH), and *V* an indicator value used as weighting. Weightings are intended in the one hand to reduce the influence of prevalent ubiquitous species and reciprocally in the other hand to increase the influence of stenocious species (species with a strong ecological significance that can live only in a restricted range of environment).

2.3. Modeling procedure

The modeling procedure was designed in two steps to highlight which spatial grain and extent in the land cover database were best correlated to the water physico-chemistry and diatom indices over the region (figure 3). Firstly, database describing water physico-chemistry, diatoms indices and the 15 spatial combinations of land cover were preprocessed using Principal Component Analysis (PCA) to summarize their information content over the region. For both water physico-chemistry and diatoms database, each variable was log-transformed to reduce the influence of outliers, then standardized by their mean and standard deviation. Land cover data were directly standardized. One PCA was applied for each 17 data matrix and the first three components of each PCA summarizing more than 60% of the total variability in the data matrix were retained for the rest of the analysis.

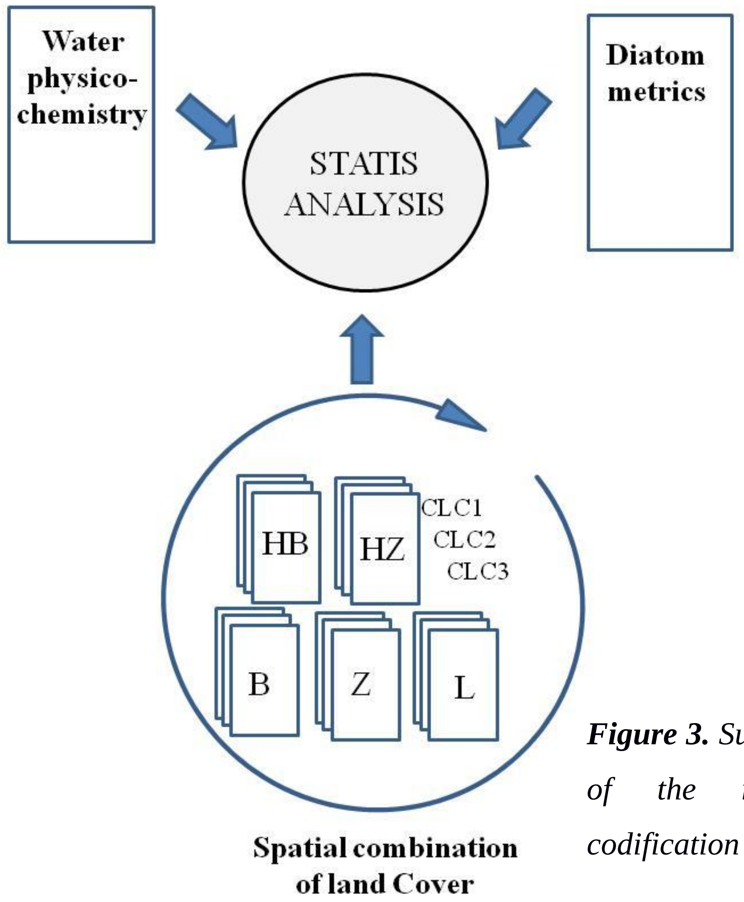

Figure 3. *Summary of the successive steps of the modeling procedure. See codification of land cover in Table 1.*

Secondly, the STATIS approach (Structuration des Tableaux A Trois Indices Statistiques; Lavit 1976; Doledec and Chessel 1994, Licandro and Ibanez 2000, Thioulouse et al. 2004) was then applied to assess the strength of the relationships between diatoms and water physico-chemistry database and each spatial combination of land cover. STATIS algorithm is an extension of co-inertia analysis (CoA) that allows the analysis of several datasets having at least one common dimension, i.e. in our case, the 53 sites. The RV coefficient of Escoufier (1973) was calculated to highlight the strength of the association between water physico-chemistry and diatoms and each spatial combination of land cover. RV coefficient ranges between 0, for a weak association, to 1, for a perfect association (Robert & Escoufier 1976). The significance of each RV values was evaluated by permuting raw data (1000 permutations) to test the null hypothesis that the association between land cover, water chemistry and diatoms was not randomly distributed in space, under a 95% level of confidence. All statistical analyses were done using the R statistical software (R Core Team Development 2008) with the ade4 library.

3. Results

Overall, the spatial associations between land cover, water physico-chemistry and diatom metrics are significant for all the spatial combinations of land cover, excepted for the lowest spatial grain (CLC1) and the lowest spatial extent (L) (table 2; figure 4; $p<0.05$; 1000 permutations). The pairwise relationships between water physico-chemistry and diatom indices ($RV\_mean_{Chemistry/Diatoms} \approx 0.40$) is higher than the relationships between land cover and water physico-chemistry ($RV\_mean_{Landcover/Chemistry} \approx 0.27$) and the relationships between land cover and diatom indices ($RV\_mean_{Landcover/Diatoms} \approx 0.19$). Globally, the higher land cover spatial extent, the stronger relationships between land cover, water physico-chemistry, diatom indices (table 2 ; figure 4; $RV\_mean_{L} \approx 0.22$; $RV\_mean_{HZ} \approx 0.23$; $RV\_mean_{Z} \approx 0.29$; $RV\_mean_{HB} \approx 0.34$; $RV\_mean_{B} \approx 0.37$). Similarly the higher land cover spatial grain the stronger relationships between land cover, water physico-chemistry and diatom indices (figure 4; $RV\_mean_{CLC1} \approx 0.25$; $RV\_mean_{CLC2} \approx 0.30$, $RV\_mean_{CLC3} \approx 0.30$, the values are not presented).

Spatial scale	$RV_{Chemistry/Diatoms}$	$RV_{Landcover/Diatoms}$	$RV_{Landcover/Chemistry}$	RV_mean	RV_mean spatial extent
B1	0.40	0.27	0.38	0.35	
B2	0.40	0.30	0.45	0.39	**0.37**
B3	0.40	0.27	0.43	0.37	
HB1	0.40	0.17	0.31	0.29	
HB2	0.40	0.28	0.42	0.37	**0.34**
HB3	0.40	0.24	0.40	0.35	
Z1	0.40	0.18	0.16	0.25	
Z2	0.40	0.23	0.28	0.30	**0.29**
Z3	0.40	0.24	0.31	0.32	
HZ1	0.40	0.05	0.09	0.18	
HZ2	0.40	0.14	0.18	0.24	**0.23**
HZ3	0.40	0.17	0.20	0.26	
L1	0.40	0.06	0.13	0.19	
L2	0.40	0.14	0.14	0.23	**0.22**
L3	0.40	0.14	0.14	0.23	
RV_mean	**0.40**	**0.19**	**0.27**		

Table 2. *Detailed RV values established for pairwise relationships between the different spatial scales of land cover and water quality metrics (physico-chemistry and diatoms).*

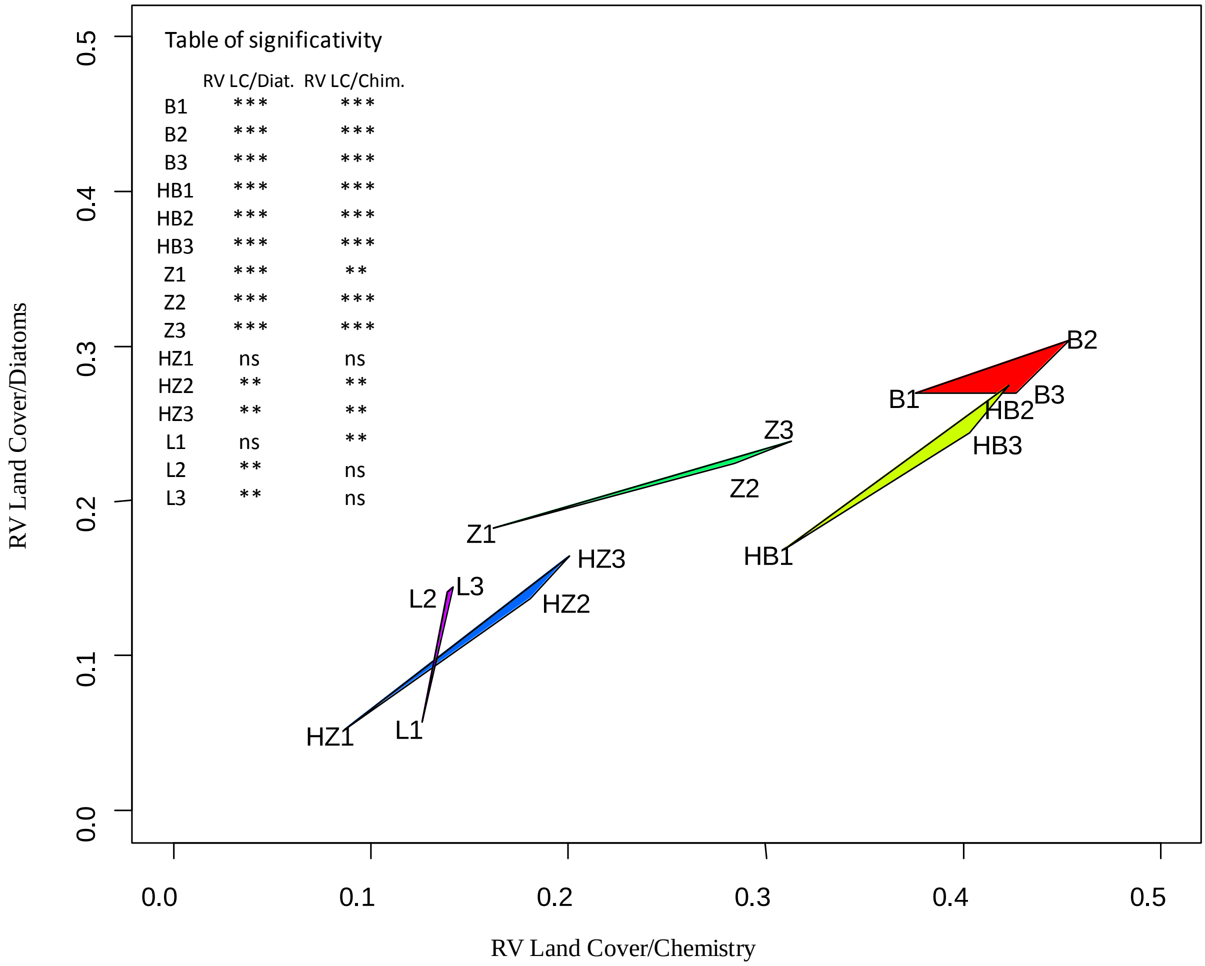

Figure 4. *Chart of the pairwise RV coefficient resulting from the STATIS analysis. Table of significativity in the top left corner. See codification of land cover in Table 1.*

The strongest relationships between land cover, water physico-chemistry and diatom metrics is obtained with the second level of Corine nomenclature (i.e., intermediate grain CLC2) extracted at the whole basin extent (i.e., B2; figure 4). For this spatial combination of land cover, the first two principal components (PC) of STATIS analysis isolate forest classes (left side) from urban (top right corner) and agricultural classes (bottom right corner; figure 5a). In regards to water physico-chemistry, the first PC also highlights an eutrophication gradient from stations with high pH and Oxygen concentration (left side) to stations with high nitrogen and organic loads (right side; figure 5b). The second PC distinguished stations with high concentrations in nitrates and suspended matter (bottom right side) from stations with high concentrations in phosphorus (PO_4^{2-}, total phosphorus), DBO and reduced nitrogen (NH_4^+, NO_2^-, top right corner; figure 5b). In regards to diatom indices, the first PC indicates a pollution gradient as all indices are oriented from the left to the right direction (figure 5c). The second PC axis separates the specialized indices (i.e., IndAuto, IndpH, IndOxy, IndSal, IndSap, indTrop) whereas global water quality indices (IPS and IBD) have a central position on this axis.

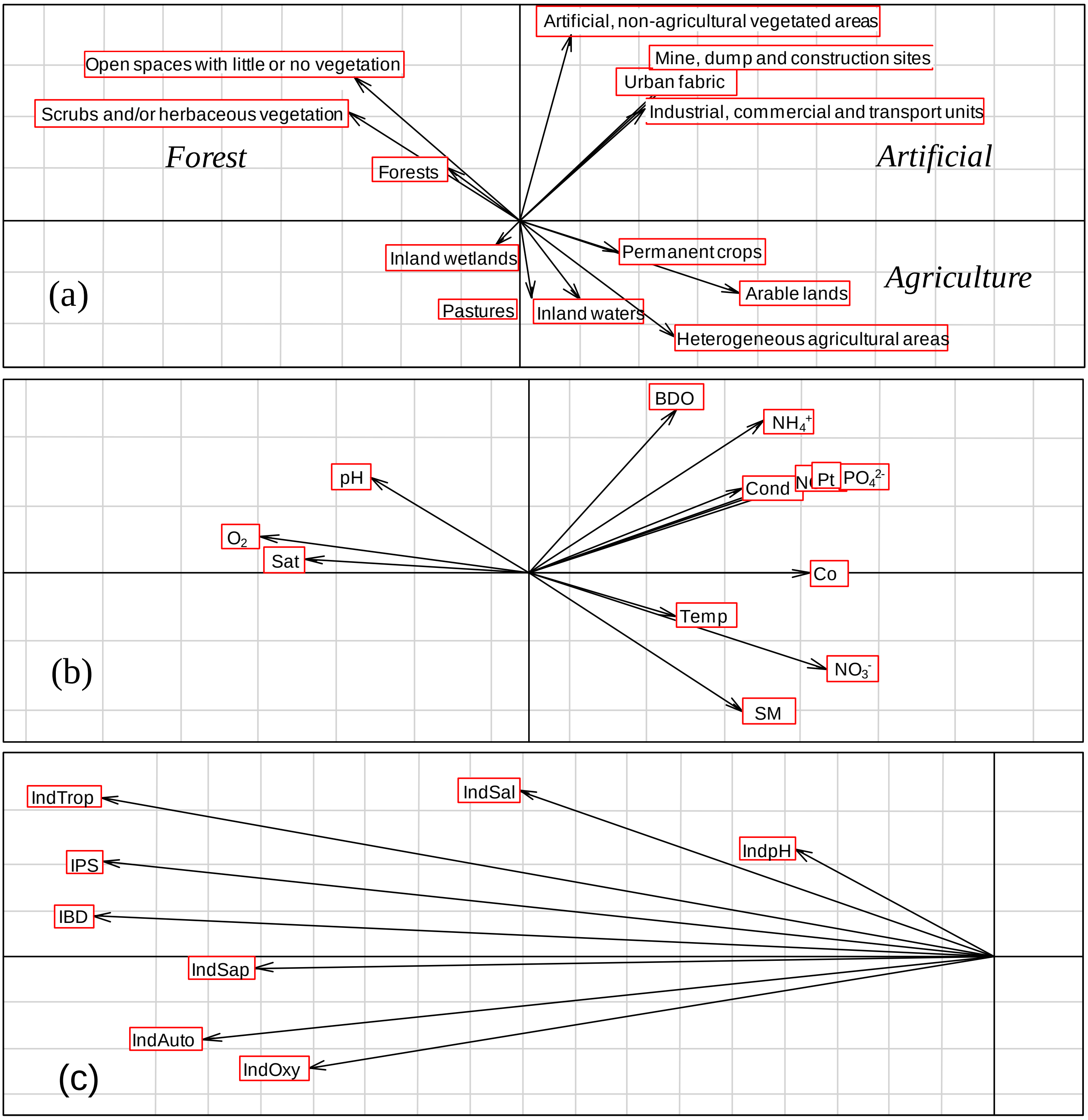

Figure 5. *PCA analyses for the land cover data pattern for the whole basin CLC2 (a) selected from the compromise analyses, for the chemistry (b), and for the diatom indices (c).*

4. Discussion

The results reported herein aimed at understanding the influence of multi-spatial land cover patterns on water quality established from chemical and biotic metrics. Because land cover patterns are not randomly distributed throughout the basin, changing the scale of the contributing area alters the relative proportion of various land cover classes (Gove et al. 2001) and, consequently, could have variable impact on stream components.

4.1. Cascade effect, from land cover patterns to diatom metrics

The data showed the hierarchical strength of the relationships between land cover, water physico-chemistry and diatom metrics. The strength of these relationships was stronger for direct connections (land cover/water chemistry and chemistry/diatom metrics) than for link established trough indirect pathways (land cover/diatom metrics; Allan 2004, King et al. 2005). Diatom literature stresses the importance of water chemistry (mainly ion concentration and trophic status) as major environmental driver of diatom distribution in stream (Soininen 2004, Urrea and Sabater 2009) while local landscape factor have a lesser effect on community structure (Passy et al. 2004, Soininen 2007). Whereas the water chemistry/diatom metric relationships are direct, the diatom communities respond by indirect pathway to land use through its effects on water quality (Stevenson 1997, Stewart and Butcher 1999). Hence, catchment determinant such as land cover, the water chemistry and the biota component are interwoven in a cascade or gradual relationship.

The overlapping carried out with the STATIS analysis pointed out a clear gradient of water quality. Landscape disturbance induced lower water physico-chemical quality inducing, in return, lower diatom index values. Whereas diatoms metrics are positively correlated to the oxygen saturation and forested land covers, the correlation is negative with the increased of both nutrient load and land cover disturbance. In the present study the water quality impairment seems to originate both from urban and agriculture area showing no single clear source of pollutant. Phosphorus load and organic matter seems to originate from urban point sources, whereas nitrates come from agricultural nonpoint sources. There is no doubt about the links between the increase of nutrient enrichment and the increase of artificial areas. Even though there is a consensus that nonpoint source pollution originate from agricultural runoff, disentangling the origin of nutrients (phosphorus and nitrates) between agriculture or urban areas is still difficult (Herlihy et al. 1998, Diebel et al. 2008). Due to interwoven mechanisms, specific relationships are problematic to determine, thus leading to frequent opposite conclusion reported in the literature. A complete understanding of these relationships depends upon the variables, the season, the driving mechanisms (Allan 1997) and the interacting influences on nutrient transport (Allan 1997, Bernard Daniel et al. 2010).

4.2. Spatial scale dependence between land cover, water physico-chemistry and diatom metrics

The influence of land cover on water chemistry and diatom metrics appeared to be scale-dependent. The strength of the relationships between the land cover at multi-spatial scales, water chemistry and diatom metrics obviously varied with scale and pointed out one major outcome. The STATIS analysis suggested that the role of land cover interaction with both water physico-chemistry and diatoms metrics increased from small to large scale.

4.2.1. Multi-scale land cover pattern and water physico-chemistry relationships: inside the controversy

Our findings from the STATIS analysis have shown that the strength of the relationships between stream water physico-chemistry and land cover patterns at the catchment extent was the strongest. The catchment extent scale being of prime importance, the overall water chemistry patterns gives evidence of environmental condition extending over the largest distance. The outcomes presented here are consistent with the continuity of the chemical processes from upper to lower reaches and the linear concept of nutrient enrichment along the stream gradient (i.e., river continnum, Vannote 1980, nutrient spiraling concept, Newbold et al. 1982). Other studies have concluded that basin wide landscape factors have strong correlations both with overall water quality or nutrient supply (Allan et al. 1997, Scott et al. 2002, Snyder et al. 2002, Williams et al. 2005). According to Scott et al. (2002), the whole basin land cover pattern explain more overall water chemistry than local scale, testifying that stream condition respond to cumulative anthropogenic impacts and to natural in-stream and allochthonous inputs (i.e., nonpoint source pollution, natural eutrophication). Moreover the importance of specific land cover class (e.g. agriculture) at large spatial scale has also been reported. For example, Omernik et al. (1981) suggested that the total amount of agricultural and forest in the catchment is more important than the vegetative composition of the riparian area. According to Johnson et al. (1997) the portion of agriculture in a catchment is of major influence on stream water quality. This trend is evident when examining water chemistry at the scale of major catchment (Johnson et al. 1997). Our data support the idea that the water quality at stream reach (i.e., sampling site) affected by nonpoint source pollution varied as a function of land cover within the watershed.

Nevertheless, the role of local *versus* broad-scales factors remain difficult to disentangle (Allan 2004) and has led to contradictory outcomes in previous studies finding a variety of significant relationships at different spatial scales (Meador & Goldstein 2003, Scott et al. 2002). Several studies frequently concluded that single scale should be considered with caution and suggested to take into account both local and larger scales. Houlahan and Findlay (2004), Vondraceck et al. (2005) and Zampella & Procopio (2009) concluded that both near and far land use provide a good measure of water quality. In other case studies, it is mentioned that the influence of the different spatial scales of land cover varied according to the season (Pan et al. 2004), the chemical parameters (Bernard Daniel et al. 2010), the river wide (Buck et al. 2004) or catchment size (Aitkenhead et al. 1999). By contrast others findings have shown that smaller spatial scales were of prime importance. Meador & Goldstein (2003) have notified that riparian conditions were positively related to the increase of water quality. Gove et al. (2001) proposed that intermediate scales of land use data generally are better predictors than local riparian or total catchment scales.

4.2.2. Multi-scale land cover patterns and diatom metrics relationships: within the consensus

Here, the statistical analysis carried out over the rivers of the Adour-Garonne basin provided evidences that the relationships between diatom metrics and land cover pattern are increasing from the smallest scales to the largest. These findings are in accordance with the conclusion frequently seen in the literature intending to explain diatom assemblages under the influence of landscape factors acting over variable spatial extents.

Stevenson (1997) has proposed a schema of “a hierarchical interrelationships among proximate, intermediate and ultimate determinant of benthic algal assemblage “. In Stevenson’s schema, land use/cover acts on algae distribution at regional or catchment scale (intermediate to ultimate factor level) in an indirect way. Pan et al. (1999), Griffith et al. (2002), Tison et al. (2005), Feio et al. (2009), as example, have concluded that broad-scale factors such as land cover explained diatom community variation. The results of Snyder et al. (2002) suggested that large spatial scale factors are more important in determining the potential benthic diatom assemblage than small scale and that proximate factors did not influence diatom community structure. Basin characteristics, such as geomorphology and land use are critical determinants of algal assemblage structure (Kutka and Richards 1996). In a comparative environmental assessment study of benthic diatom, macroinvertebrates and fish communities, Passy et al. (2004) has reported that the role of small-scale habitat and habitat-land cover interaction increase across the diatom, macro-invertebrate and fish assemblages whereas the effect of large-scale land cover declined.

4.2.3. Relevancy of land-cover spatial grain

The majority of studies dealing with land cover take into account the coarsest spatial grain, namely urban, agricultural (subdivided between crops and pastures), and forest classes with secondarily water bodies and wetlands. Contrasting with a large number of studies dealing with landscape ecology, the relative relevancy of the different levels of spatial grain is rarely subject of consideration. Herlihy et al. (1999) concluded that the use of fourteen land cover subclasses rather than five broad classes did not greatly improved relationships with stream chemistry. Conversely, Goldstein et al. (2007) established that "more refined classifications of land cover would probably improve attempts to relate land use to stream ecosystems". Here, our findings seem to be a compromise between the broad and narrow classification. When using fifteen subclasses (CLC2) in place of five (CLC1), the strength the relationships between both chemistry and diatom metrics notably increased. In parallel, the highest detailed level of Corine (44 classes, CLC3) did not improved the strength of the relationships.

The relevance of land cover classification might be closely linked with land cover diversity. High land cover diversity coupled with a broad geographical scale and large data set would give more accuracy to a refined classification. On the contrary, homogeneous land cover pattern would give less relevance to detailed land cover subclasses. The study of Herlihy et al. (1999) and Goldstein et al. (2007) comfort such hypothesis. In Herlihy et al. (1999), the data set is located in the Appalachian Mountains, whereas in Goldstein et al. (2007) the study sites as part of the NAWQA Program (National Water Quality Assessment Program) distributed across the United States. In our case study, the sampling sites are distributed across a broad diversified geographical area (9 hydroecoregions) with various land cover classes. Nevertheless, the limited data set used in the present study (53 stations) explains the fact that many land cover classes of the Corine level 3 have a very low part. As consequence, CLC2 appeared to be the best compromise between richness (number of subclasses) and diversity (representation) of land cover pattern.

4.3. Perspective to improve diatom-based monitoring tool

This study provides some relevant perspective to key-questions concerning diatom-based monitoring tools, particularly with regards to the Water Framework Directive implementation.

The current European legislation bases the water quality assessment on the Ecological Quality Ratio (EQR) that is the difference between theoretical diatom indices at reference condition and observed diatom indices at stream reach. This method enables to predict how water quality should be like out of any anthropogenic pressure (Tison et al. 2007). At the present time, the land cover dataset is the only usable consistent information assessing the potential landscape pressures on running waters. Thus, our core suggestion is that taking into account the observed land cover pattern might be a next promising approach for the improvement of diatom-based biomonitoring methodologies. For instance, it might be possible to build-up a landscape disturbance metric, based on the ratio between natural versus artificial landscape area at the catchment extent. The combination between this landscape disturbance metrics and the existing EQR approach could give information with regard to both theoretical natural condition and potential anthropogenic pressure.

Whereas chemical water quality impairment mainly originates from a double pressure acting simultaneously, namely point source and nonpoint source discharge, the main problem keep on ranking these two causes of impact in order of their importance. To disentangle these two aspects could be subject of controversy. For example Feio et al. (2009) considered that the environmental condition at catchment scale had a greater influence over the water quality and the diatom communities than the most immediate activities. On the contrary Tison et al. (2005) concluded that the pollution affecting the sampling station is more influential on the diatom communities than the natural conditions whose are overwhelmed. Moreover, it appears that agricultural land uses often exert their influence at the whole catchment scale, while disturbance associated with urbanization might be more important immediately adjacent to a watercourses (Brazner et al. 2007). Determining the relative influence of diffuse *versus* point source pollution is a crucial issue in the targeting and the implementation of river management programs, particularly in order to restore the good ecological status as required by the WFD. To resolve this issue represent a challenging prospect.

5. Conclusion

In the present study we have determined the spatial scale of land cover that best explained jointly the water physico-chemistry and the diatom metrics in a major river system, revealing three key-findings. First, the increased strength of the relationships between land cover *vs* physico-chemistry, physico-chemistry *vs* diatoms metrics and land cover *vs* diatoms metrics stressed the continuity of processes along the gradient and their cumulative impacts. These results thus confirmed that the diatom metrics respond to land cover patterns through the water physico-chemistry by indirect pathways across the largest spatial extent along a "cascade effect". Second, we have established that the land cover patterns at the catchment extent have the strongest influence on the water quality at a stream reach than the local or intermediate (corridor or sub-basin) landscape extent. This outcome is accurate in the context of pollution originating from nonpoint source during summer base-flow period. Third, the intermediate spatial grain of Corine land cover (i.e., CLC2) appeared to be the best compromise between richness (number of sub-classes) and diversity (representation) of land cover pattern.

These findings provide relevant information to key-question concerning diatom-based monitoring programs as promoted by the Water Framework Directive. We concluded that in the scope for the improvement of biomonitoring methodologies, taking into account the potential landscape disturbance toward land cover pattern metric at the catchment scale might be a next promising approach.

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CHAPITRE 4

Influence of small-scale gold-mining on French Guiana streams: Are diatom assemblages valid disturbance sensors?

[Accepted] | Ecological Indicators

Influence des sites d'orpaillage de petite dimension sur les ruisseaux de Guyane française : les assemblages diatomiques sont-ils des capteurs valides des perturbations ?

Résumé

En Guyane française, depuis une dizaine d'années, le nombre de sites illégaux d'orpaillage est en très forte hausse causant des dommages environnementaux considérables. L'extraction de l'or consiste à laver le sol avec des jets d'eau à haute pression entrainant la déforestation des sites d'exploitation, l'érosion des sols, le rejet de métaux lourds et d'hydrocarbures. Les sites d'orpaillage sont localisés à proximité des cours d'eau qui vont alors collecter les effluents surchargés en toxiques et en matière en suspension. L'impact du relargage du mercure dans le milieu, utilisé pour fixer l'or, a donné lieu à de nombreuses investigations. A l'inverse, peu d'attention a été portée à l'érosion des sols qui pourtant reste la conséquence la plus visible à long terme, la plus répandue et probablement la plus traumatisante pour les cours d'eau.

L'objet de cette étude était d'examiner les conséquences des activités d'orpaillage dues à l'exploitation de sites miniers illégaux de petite dimension sur les communautés de diatomées benthiques. Les stations d'échantillonnage ont été positionnées dans trois types de cours d'eau aux caractéristiques hydromorphologiques similaires mais impactés par des degrés différents d'orpaillage : des sites de référence sans activité, des sites dont l'activité d'orpaillage est ancienne et des sites en cours d'exploitation. Tous les sites sont localisés dans la réserve naturelle des Nouragues.

Dans une première phase, l'étude des diatomées s'est portée sur la composition taxonomique des assemblages. Dans un second temps, nous avons testé si les activités d'orpaillage affectaient la structure fonctionnelle (forme de vie) des assemblages. Une attention particulière a été portée aux capacités de mouvements des diatomées. Nous avons émis l'hypothèse que plus les diatomées sont mobiles plus elles sont capables de tolérer des charges significatives de matière en suspension, alors que les formes immobiles ont peu de chance de survie dans des conditions de forte turbidité et de dépôt important de sédiments.

En raison de l'insuffisance des connaissances taxonomiques des diatomées de Guyane, la détermination taxonomique s'est faite au niveau du genre. Une distinction a été faite entre trois formes de vie : les formes épontiques vivant fermement attachées au substrat, les formes benthiques dont l'adhésion au substrat est moins forte et les formes planctoniques ; les capacités de fixation étant réciproquement liées à la capacité motrice des diatomées.

Au total quarante trois genres ont été identifiés. Dans les sites de référence, les assemblages de diatomées sont dominés par des diatomées non mobiles alors que dans les sites en cours d'exploitation les formes mobiles sont dominantes. Quant aux sites anciennement orpaillés, ils combinent les formes benthiques et les formes épontiques.

En dépit des conditions extrêmes, les communautés persistent et la diversité taxonomique semble peu affectée. Nos résultats ont montré que la structure taxonomique et fonctionnelle des assemblages diatomiques était influencée par l'intensité de l'orpaillage. De plus, il est confirmé que malgré l'arrêt des activités d'orpaillage depuis plusieurs mois, la récupération des milieux est incomplète. L'hypothèse de départ a été confirmée en démontrant l'existence d'une relation significative entre l'érosion du sol, la distribution des formes de vie et les capacités motrices des diatomées. D'autre part, aucune forme tératologique de diatomées (déformation des valves, altération de l'ornementation) n'a été observée, ne permettant pas de conclure quant à une pollution significative par rejets de métaux lourds.

Ainsi, ces résultats ont démontré que les assemblages diatomiques étaient sensibles aux perturbations dues à l'orpaillage et suggèrent que les communautés de diatomées peuvent être utilisées comme capteur du stress environnemental causé par les activités d'orpaillage produites par de petites exploitations. Nous concluons que le ratio formes mobiles (benthiques) versus formes immobiles (épontiques) constitue un indicateur pertinent de quantification du degré de perturbation. Parallèlement, la prise en compte des capacités motrice des formes mobiles peut s'avérer être une approche permettant d'estimer la dynamique de sédimentation (plus les diatomées sont animées de mouvements complexes et plus la sédimentation est intense).

Influence of small-scale gold-mining on French Guiana streams: Are diatom assemblages valid disturbance sensors?

Loïc Tudesque, Gaël Grenouillet, Muriel Gevrey, Kamran Khazraie and Sébastien Brosse

Abstract

The ongoing gold-rush in French Guiana could cause severe disturbance to ecosystems. Although illegal, small gold-mining sites are rapidly expanding. Few studies have attempted to measure the consequences of the increased gold-mining on the biota of small forest streams, and to date, no study has dealt with primary producers. Here we measured the response of diatom assemblages to gold-mining in ten sites differently affected by the mining activity (i.e., reference, formerly gold-mined and currently exploited). Our results showed that both taxonomic and functional structure of the diatom assemblages were influenced by the intensity of gold mining activity. A significant relationship between soil erosion and diatom motility ability has been demonstrated. These findings show that diatom assemblages are sensitive to gold-mining disturbance and suggest that diatom communities may be used as sensors of the environmental stress caused by small-scale gold-mining activities.

Keywords: biomonitoring ; diatom ; French Guiana ; life-form ; mining ; motility ; recovery ; turbidity

1. Introduction

Tropical ecosystems are threatened by human activities (Cincotta et al., 2000; Lorion and Kennedy, 2009; Portillo-Quitero and Sánchez-Azofeifa, 2010), which are causing profound disturbance of the forests and loss of biodiversity (Lawton et al., 1998). French Guiana, which has 90% of rainforest coverage, and includes tropical wilderness area covering upper Amazonia and the Guiana Shield, is no exception (Mittermeier, 1988). In French Guiana, the increase in the anthropogenic pressure originates mainly from gold-mining.

During the last decade, gold-mining activities, and especially illegal mining sites, are increasing exponentially which could lead to considerable environmental damage (Hammond et al., 2007). The extraction of gold deposits consists of washing the soil with high pressure water jets, leading to major environmental impacts, such as deforestation, soil erosion and heavy metal pollution (Cleary, 1990). The gold-mining sites are located along rivers that collect all the effluents overloaded with suspended matter and toxicants, such as mercury, which is used to recover gold from the sediment (Watts et al., 2003). The mercury released into the environment impacts aquatic ecosystems, including the primary producers (Anson Moye et al., 2002; Kelly et al., 2007), macroinvertebrates (Henny et al., 2005; Žižek et al., 2007) and fish (Barbosa et al., 2003; Sampaio da Silva et al., 2009). Little attention has been paid to other potential impacts including soil erosion, which is more visible and is probably the most pervasive and devastating consequence in the short term (Hammond et al., 2007). Experimental evidence indicates that the turbidity generated by fine sediment can affect stream productivity (Parkhill and Gulliver, 2002; Izagirre et al., 2009) and species interactions (Utne-Palm, 2002; Pekcan-Hekim and Lappalainen, 2006). In fact, siltation and the subsequent biological impairment are among the most prevalent problems in streams and rivers throughout the world (Pimentel and Kounang, 1998).

In French Guiana, the National Forestry Office estimated that 1333 km of watercourses were directly affected by gold mining, as well as 12,000 ha of forest (CIRAD-ONF, 2006; Mansillon et al., 2009). The number of illegal mining sites in French Guiana is unknown, but estimated between 500 and 900 sites. There is little information, however on the overall impact of gold-mining activities (Mol and Ouboter, 2004; Mendiola, 2008; Yule et al., 2010), especially for the most abundant and widespread type of gold extraction in the Guiana shield, namely illegal small-scale gold mines (Hammond et al., 2007). As the rivers of the Guiana shield are characterised by some of the lowest levels of natural suspended solids in the world (Hammond et al., 2007), the potential impact of increased turbidity and siltation due to mining could therefore be profound.

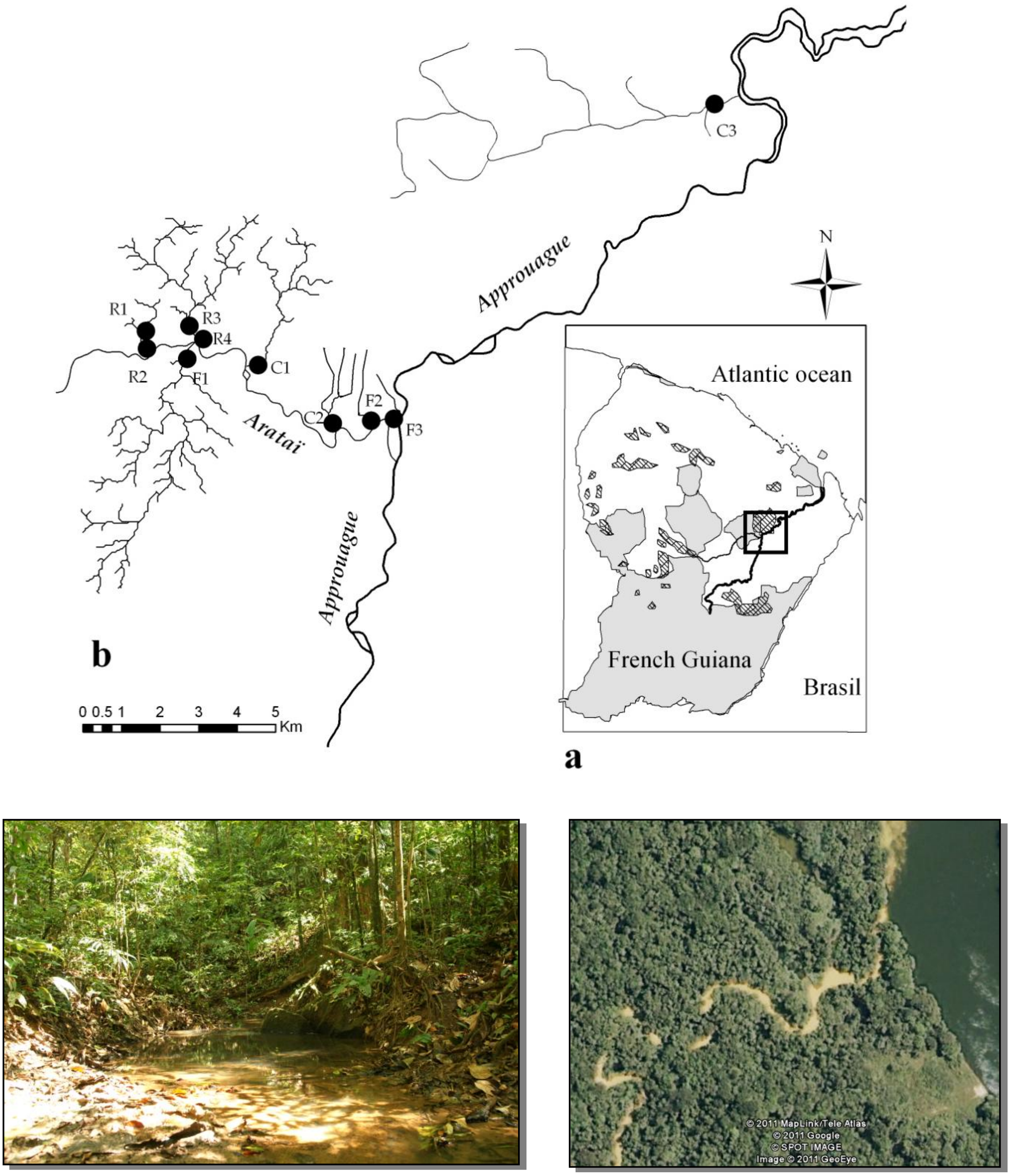
Our purpose was to investigate how small mining sites affect biota in small forest streams of French Guiana. We chose streams with similar hydromorphological features, but that were affected by various degrees of gold-mining intensity (reference, formerly gold-mined and currently exploited). We focussed on diatoms that colonise almost all aquatic ecosystems (Round et al., 1990) and that are recognized as efficient bioindicators (Prygiel and Whitton, 1999; Stoermer and Smol, 1999). We tested whether gold-mining affects both the taxonomic and the functional structure of diatom assemblages. We hypothesized that motile diatoms are able to tolerate the high load of suspended solids generated by gold-mining, whereas non-motile life-forms may have little chance of survival under high load of sediment. This aimed to assess whether the diatoms could be valuable sensors to monitor streams impacted by small-scale gold-mining activities.

2. Methods

2.1. Study area

The study area was located in the Approuague Basin (French Guiana). Nine sampling sites were located in the Nouragues Nature Reserve, in small tributaries of the Arataï river (tributary of the Approuague), and one site outside and downstream of the reserve, in a tributary of the Approuague river (Fig.1; Table 1). These streams were low order primary forest streams of similar size (less than 5 metres wide).

To assess the effect of gold mining activities on diatom communities, we identified and selected sites with three different levels of gold mining intensity: i) reference sites (sites R1 to R4) which had never been exploited; ii) formerly exploited sites (F1 to F3) where gold-mining activity had been recorded during the year before sampling, but had not been exploited for at least 6 months; and iii) currently exploited streams (C1 to C3), which were under exploitation during field sampling. In order to get an immediate assessment of the physical impact on the streams, we measured the turbidity with a WTW field turbidimeter.



c Sampling site R4 **d** Sampling site C3

Figure 1. *Location of sampling sites. a) Map of French Guiana indicating the location of the study area (black square). The biodiversity reserves (grey) and the gold mining areas (hatched) are also indicated. Note that some mining areas are located inside the biodiversity reserves. b) Detailed map of the study area indicating the sampling sites: R1, R2, R3 and R4: reference sites; F1, F2 and F3: formerly exploited sites; C1, C2 and C3: currently exploited sites. C) Sampling site R4. D) Sampling site C3.*

Vigouroux et al. (2005) showed that turbidity was an accurate proxy of overall gold mining intensity (heavy metals, decrease of light intensity, increase of siltation). Together with an increase of turbidity, gold mining also causes an increase of siltation, due to the deposition of the fine mineral material on the river beds (EPA, 2000; Vigouroux et al. 2005).

The sampling sites were located close to the confluence with the main river (Approuague or Arataï) and hundreds of meters downstream from the areas of illegal mining. The sites are therefore the catchment outlet and drain all the effluents produced by the mining activity.

Sites	Gold mining	Latitude	Longitude	Turbidity (NTU)
R1	No	52°40'31"O	04°02'12"N	3.1
R2	No	52°40'31"O	04°02'11"N	3.6
R3	No	52°39'25"O	04°02'12"N	3.0
R4	No	52°39'19"O	04°02'10"N	3.6
F1	Fomer	52°39'52"O	04°02'07"N	4.1
F2	Fomer	52°34'08"O	03°59'44"N	5.0
F3	Fomer	52°33'50"O	03°59'59"N	4.3
C1	Current	52°37'38"O	04°01'31"N	41
C2	Current	52°35'13"O	03°59'37"N	201
C3	Current	52°23'42"O	04°09'27"N	237

Table 1. *Geographical location, gold mining activity and turbidity (NTU, Nephelometric Turbidity Unit) of the ten sampling sites.*

2.2. Sampling and treatment procedures

The samples used for diatom analysis came from periphytic material collected in November, during the dry season. Diatoms can be found on most submerged surfaces but the recommended substrate/habitat combination to sample diatoms are stones obtained from a riffle with a flowing current (Kelly et al., 1998; AFNOR, 2000). Owing to the difficulty of finding the same substrate in all the sampling sites, we systematically investigated two different substrates: stones (S) if available, wood (W) and/or submerged leaves (L). In accordance with Townsend and Gell (2005), the genera composition did not differ between substrates. The samples were coded with the station code (R, C, F), site number (1 to 4) and substratum (S, W or L).

The sampling protocol consisted of brushing material from hard and stable substrates into a clean container and then storing the material in a flask. Samples were then fixed with buffered formaldehyde. At the laboratory, samples were cleaned in boiling hydrogen peroxide and hydrochloric acid. After removing all traces of hydrochloric acid, the diatoms were dried onto cover slips and fixed on microscope slides using a high-refractive index resin (Naphrax®, R.I.=1.7) to obtain permanent slides.

2.3. Taxonomical and ecological data

We identified and counted the relative abundance of the diatom taxa. Counting (400 valves) was carried out using an Olympus BX51 differential interference contrast microscope (DIC) with 1000X magnification under oil immersion. The identification of the diatom flora was done to the genus level following to Round et al. (1990), Krammer and Lange-Bertalot (1991-1997) and Metzeltin and Lange Bertalot (1998, 2007). A more accurate identification (i.e., species level) was not feasible due to the current limited knowledge of the diatom flora of French Guiana.

The genus level was nevertheless sufficient to sort genera according to their motility performance. Indeed, the taxonomical dichotomies leading to the identification of the genus level are based on the cell symmetry, the presence or not of a raphe system and its course. These generic features determine the diatom life-forms and throw light on their motility ability. Many studies have concluded that the raphe system accounts for diatom motion (Edgar 1982; Bertrand 1990, 1992, 2008; Round et al 1990), and Coste (in Cemagref, 1982) and Hill et al., (2001) demonstrated that the genus level is sufficient to determine the motility ability of the diatoms. A distinction has thus been made between three life-forms of periphytic diatoms mainly according to Denys (1994) and completed by Round et al. (1990): i) epontic life-form referring to taxa that are not motile and firmly attached to any kind of substrate; ii) benthic life-form are motile and live on the substrate and iii) euplanktonic life forms are not motile and live in the water column.

2.4. Data analysis

The data were analyzed using R statistical software (R Core Team Development, 2008). To determine taxonomical similarities between the samples and to promote site typology, sampling sites have been classified through a hierarchical cluster analysis using Ward’s linkage method with Bray and Curtis distance measure. The Mean Split Silhouette (MSS) criterion (Pollard and van der Laan, 2002) and the Multiple Response Permutation Procedure (MRPP) (Mielke et al., 1976) were used to validate the clustering relevance. The

MSS value determines the optimal level of the classification tree where the clusters are the most homogenous. On the other hand, the MRPP analysis tests if the differences between the clusters are significant.

An indicator genus for each group of site typology was identified according to the Dufrêne and Legendre (1997) Indicator Value (IndVal). Taxonomical units having the highest IndVal score were used to discriminate the clusters. The statistical significance of the indicator values was evaluated using a randomization procedure with 500 permutations. Processing was done with the function ‘duleg’ of the package ‘labdsv’ (Dufrêne and Legendre, 1997).

To assess the effects of environmental characteristics on variation in diatom composition, we carried out a non-parametric MANOVA (McArdle and Anderson, 2001), an analysis of variance using distance matrices performed by the function ‘adonis’ of the package ‘vegan’ (Oksanen et al., 2008). This function partitions sums of squares using metric or semimetric distance matrices. The significance of the test was given by *F*-tests based on sequential sums of squares from 1000 permutations of the raw data.

3. Results

A total of 43 genera were identified. The number of genera identified at each site ranged from 11 to 27 (Table 2). The following genera had greater than 20% abundance in at least one sample: *Achnanthidium* Kützing, *Aulacoseira* Thwaites, *Encyonema* Kützing, *Eunotia* Ehrenberg, *Fragilaria* Lyngbye, *Gomphosphenia* Lange-Bertalot, *Navicula* Bory de Saint Vincent, *Nupela* Vyverman & Compère, *Nitzschia* Hassall and *Surirella* Turpin. The average composition of the diatom communities was made up of 55% epontic life-forms and 44% benthic life-forms, whereas the remaining 1% represented euplanktonic forms. Differences in diatom taxonomic and life-form composition between samples were significantly explained by stream status (R, F or C) (non-parametric MANOVA, $P<0.002$ and $P=0.01$, respectively, Table 3), but not clearly by substratum ($P=0.58$ and $P=0.027$, respectively).

GENERA	Life form	R1	R2	R3	R4	F1	F2	F3	C1	C2	C3
Adlafia Moser, Lange-Bertalot & Metzeltin	Benthic		X			X					
Amphora Ehrenberg	Benthic						X				
Brachysira Kützing	Benthic				X		X	X	X	X	X
Caloneis Cleve	Benthic		X		X						
Capartogramma Kufferath	Benthic		X			X	X				
Chamaepinnularia Lange-Bertalot & Krammer	Benthic							X	X	X	
Craticula Grunow	Benthic			X						X	
Cymbopleura Krammer	Benthic						X				
Diadesmis Kützing	Benthic	X	X		X		X	X			
Diploneis Ehrenberg	Benthic				X	X	X	X			
Eolimna Lange-Bertalot & Schiller	Benthic		X		X		X			X	
Fallacia Stickle & Mann	Benthic		X		X		X				
Frustulia Rabenhorst	Benthic	X		X	X	X	X	X	X	X	X
Geissleria Lange-Bertalot & Metzeltin	Benthic				X						
Germainiella Lange-Bertalot & Metzeltin	Benthic		X								
Gyrosigma Hassall	Benthic					X		X	X		X
Hippodonta Lange-Bertalot, Metzeltin & Witkowski	Benthic		X			X					
Kobayasiella Lange-Bertalot	Benthic								X		
Luticola Mann	Benthic		X	X		X	X	X		X	
Naviculadicta Lange-Bertalot	Benthic		X		X	X			X		
Navicula Bory de Saint Vincent	Benthic	X	X	X	X	X	X	X	X	X	X
Neidium Pfitzer	Benthic									X	
Nitzschia Hassall	Benthic	X	X	X	X	X	X	X	X	X	X
Orthoseira Thwaites	Benthic		X					X			
Pinnularia Ehrenberg	Benthic	X	X		X	X	X	X		X	X
Placoneis Mereschkowsky	Benthic		X								
Stauroneis Ehrenberg	Benthic	X	X	X			X		X		
Stenopterobia Brébisson	Benthic			X		X	X	X	X	X	
Surirella Turpin	Benthic			X	X	X	X	X	X	X	X
Staurosira Williams & Round	Epontic		X				X				
Achnanthes Bory de Saint Vincent	Epontic		X	X		X		X			
Achnanthidium Kützing	Epontic	X	X	X	X		X	X	X	X	X
Cocconeis Ehrenberg	Epontic		X		X	X	X				
Encyonema Kützing	Epontic	X	X	X		X	X		X	X	X
Eunotia Ehrenberg	Epontic	X	X	X	X	X	X	X	X	X	X
Fragilaria Lyngbye	Epontic		X	X	X		X	X	X	X	X
Gomphonema Ehrenberg	Epontic	X	X	X	X	X	X	X	X	X	X
Gomphosphenia Lange-Bertalot	Epontic		X		X						
Nupela Vyvermann & Compere	Epontic	X	X		X	X	X	X			
Terpsinoe Ehrenberg	Benthic		X								
Aulacoseira Thwaites	Euplanktonic						X		X		
Centrophycidae undetermined	Euplanktonic							X			
Cyclotella Kützing	Euplanktonic						X				
Number of genera		11	27	14	20	19	26	20	17	17	12

Table 2*. Inventory at the genus level of the diatoms and their life-form. Sample site codes: R= reference ; F= formerly exploited ; C= currently exploited ; 1-4 correspond to sites.*

The percentage of benthic forms was greatest in currently exploited sites (C), whereas the reference and formerly exploited sites had values less than 50%. Furthermore, the relative abundance of the benthic forms was lower in the reference sites than in the formerly exploited sites (Fig. 2).

	MS	*F*	R^2	*P*	
(a)					
Subtratum	0.161	0.858	0.078	0.580	*ns*
Status	0.596	3.178	0.288	0.002	**
Residuals	0.188		0.634		
(b)					
Subtratum	0.153	4.743	0.260	0.027	*
Status	0.210	6.483	0.356	0.010	**
Residuals	0.032		0.384		

Table 3. Non-parametric MANOVA assessing the effects of substratum and gold-mining (stream status: reference; formerly exploited; currently exploited) on variations in (a) taxonomic and (b) life-form similarity between sites. The significance of the tests was checked using *F*-tests based on sequential sums of squares from 1000 permutations of the raw data.

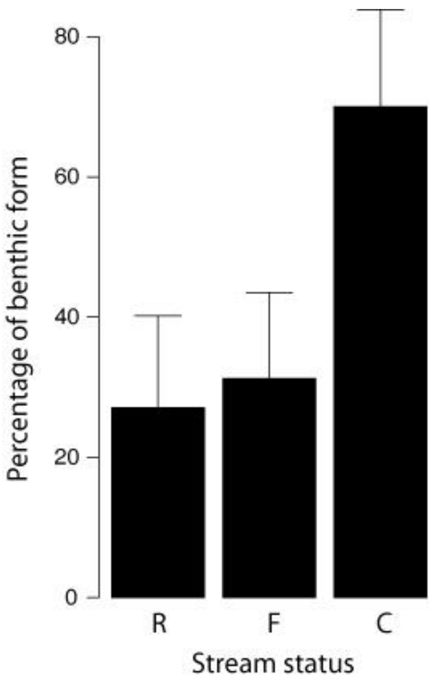


Figure 2. *Percentage of benthic forms in reference (R), formerly (F) and currently (C) exploited (C) streams.*

In addition, the hierarchical clustering based on life-forms distinguished two clusters (Fig. 3), whereas clustering based on taxonomy discriminated five clear subsets (Fig. 4). These typologies, based on taxonomical and biological trait clearly separated the sites according to their level of impairment. Reference sites (two clusters), former (two clusters) and current sites (one cluster) were clearly separated with the taxonomical typology, whereas formerly exploited sites were mixed in the life-form typology.

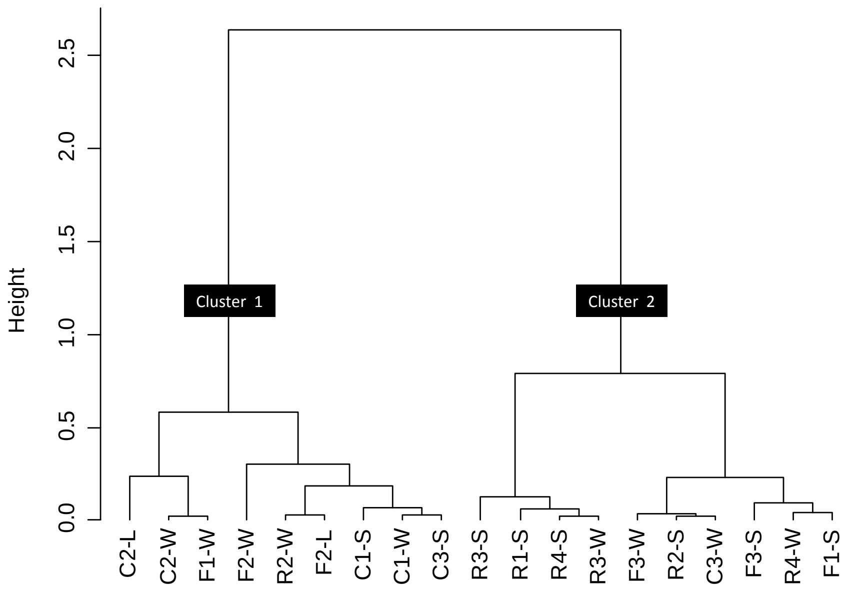


***Figure 3**. Hierarchical clustering (Euclidean distance; Ward algorithm) of the sampling sites based on diatom life-forms. R1, R2, R3 and R4: reference sites; F1, F2 and F3: formerly exploited sites; C1, C2 and C3: currently exploited sites. The substrata are indicated after the site labels: W: Wood; S: Stone; L: Leaves.*

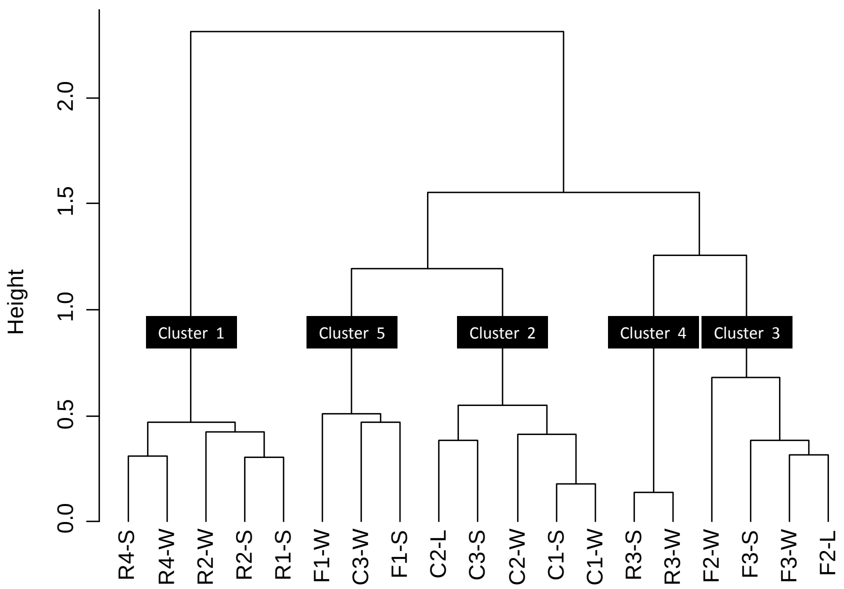


***Figure 4**. Hierarchical clustering (Euclidean distance; Ward algorithm) of the sampling sites based on diatom genera. R1, R2, R3 and R4: reference sites; F1, F2 and F3: formerly exploited sites; C1, C2 and C3: currently exploited sites. The substrata are indicated after the site labels: W: Wood; S: Stone; L: Leaves.*

Species indicator values (IndVal) were calculated for each diatom genus. Among them, ten had a significant ($p<0.05$) score and were significant representatives of each set of samples defined by the taxonomical typology (Table 4).

Indicator genus	Cluster	IndVal	Probability
Nupela	1	0.900	0.002
Caloneis	1	0.600	0.034
Surirella	2	0.779	0.002
Brachysira	2	0.547	0.026
Navicula	2	0.403	0.036
Eunotia	3	0.620	0.002
Pinnularia	3	0.567	0.022
Achnanthidium	4	0.692	0.004
Encyonema	5	0.608	0.028
Hippodonta	5	0.515	0.042

Table 4. Significant indicator genera (IndVal, $p < 0.05$) for each cluster.

Concerning the two clusters of reference sites (cluster 1 and 4), indicator taxa were the *Nupela*, *Caloneis* and *Achnanthidium* genera respectively. In the case of the formerly exploited sites (clusters 3 and 5) the main representative genera were *Eunotia*, *Pinnularia*, *Encyonema* and *Hippodonta*. *Surirella* pooled with *Navicula* and *Brachysira* is clearly characteristic of currently exploited sites (cluster 2).

In the reference sites, the diatom assemblages were dominated by non-motile diatoms (epontic taxa; i.e., *Achnanthidium*, *Nupela*, *Eunotia*, *Gomphonema, Gomphosphenia* genera). Conversely the motile benthic life-forms were dominant in the currently exploited sites. The diatom communities of formerly exploited sites combined benthic and epontic forms, nevertheless benthic diatoms remained dominant. Among these communities, we identified the *Achnanthidium*, *Eunotia*, *Encyonema*, *Frustulia*, *Gomphonema*, *Navicula* and *Nitzschia* genera.

4. Discussion

The current knowledge of the overall impact of gold mining activities on the aquatic fauna is limited and to our knowledge, our study is the first reporting the effect of gold mining on diatom flora. Indeed, almost all studies in neotropical environments have been on fish assemblages (Mol and Ouboter, 2004; Mendiola, 2008). Of these studies, only Mol and Ouboter (2004) have dealt with the impacts of small-scale gold mines in the neotropics. The results of these fish studies are consistent with our findings on diatoms, as both studies demonstrated that gold mining does not induce a sudden decline in genera richness, but profoundly affects assemblage compositions (Mol and Ouboter, 2004; Mendiola, 2008). Such a consistent response across trophic levels (i.e., diatoms and fish) suggests that gold mining may affect the entire food web (Yule et al., 2010) and is known to induce a decline in the taxonomic and functional diversity of fish (Tarras-Wahlberg et al., 2001), macroinvertebrates (Milner and Piorkowski, 2004) and primary producers (Quinn et al., 1992).

Although the mining activities we considered here were small-scale operations involving only a few workers and no heavy equipment (the miners cross the forest on foot with their equipment), the resulting impact was sufficient to exceed the resistance threshold of the stream. As a direct consequence, we observed that currently, formerly and reference sites host distinct diatom assemblages. Thus, we confirmed that stream recovery was still incomplete several months after the cessation of gold-mining activities. Our results are consistent with those of Yule et al. (2010) on an Indonesian river, where the extent of the recovery 10 months after the mining ceased depended on the duration of the mining activities and on the severity of the perturbation.

Gold mining generates two main disturbances due to soil erosion: increase of the load of suspended solids (i.e., water turbidity) and heavy metal release (Hammond et al. 2008; Yule et al. 2010). In order to disentangle the impact of toxicant and of suspended solid load, we paid particular attention to diatom deformity. It is known that under long-term and or high exposure of heavy metals, the diatom communities present abnormal forms (Riggiu et al., 1998; Falasco et al., 2009; da Silva et al., 2009; Duong et al., 2010). As no diatom deformity was recorded, the changes of the diatom flora mainly responded to suspended solids load, inducing turbidity and siltation, rather than heavy metals load.

Diatom assemblages are recognized to be relevant indicators of sediment stability and sediment hydrodynamics (Sylvestre et al., 2004; Méléder et al., 2007). Consequently, the distribution of the diatoms genera according to the degree of impairment was strongly influenced by their differential motility ability which determines their ability to deal with substratum stability and is closely linked to siltation dynamic. This gradient is limited at one end by non-motile attached diatoms and at the other end by extremely motile diatoms, such as *Surirella*, able to adapt to extremely unstable substrates. The literature gives details of variable motility performance observed among benthic forms. For instance, the *Gyrosigma* Hassall, *Nitzschia* and *Surirella* genera with high motility (Round et al., 1990; Bertrand, 1992) reflect an important dynamic of siltation or sediment instability whereas *Navicula* and *Frustulia* indicate moderate siltation and stable sediment (Sylvestre et al., 2004). The *Encyonema* and *Eunotia* genera with moderate mobility would testify for transitional conditions indicative of recovery dynamics.

This finding suggests that diatoms may be of value in measuring the impact of current and past gold mining activities on streams. In the rivers of Montana USA, Bahls (1993) used a siltation index based on the proportion of motile species adapted to hold their position in unstable substrates. This index only takes into account the percentage of the dominant motile *Navicula* and *Nitzschia* genera. Our findings, combined with those of Bahls (1993), suggest that the proportion of benthic *versus* epontic diatoms might be a useful tool to assess the degree of siltation. An increase in the benthic life-forms in any samples therefore means an increase in siltation, and as a consequence, a downgrading of biogenous water quality. Hence, periphytic diatom communities provide evidence of the various degrees of impairment due to gold-mining activity and in many ways could testify to resilience (Harrison, 1979) and to the recovery process (Neubert and Caswell, 1997). They are therefore good candidates to set up a "diatomic tool" to assess and monitor the degree and the dynamics of disturbance on neotropical stream ecosystems subjected to soil erosion caused by gold mining activities.

5. Conclusions

Our results showed that the use of the diatom genera was efficient to assess the effect of gold mining activity, acting both on diatom assemblages and functional traits. The diatom motility ability appeared to be of prime importance in order to determine soil erosion intensity due to gold-mining. We concluded that the relative abundance of the motile benthic life-forms *versus* non-motile epontic forms would be a significant indicator to quantify the degree of impairment.

In addition, taking into account the motility ability of significant indicative benthic genera would be a promising approach to assess the temporal dynamic of siltation. Considering life-form distribution among assemblages, and motility ability of dominant benthic genera, make it possible to estimate quantitative effect and recovery *vs.* impairment dynamic respectively. Consequently, the diatom flora has proved to be a valuable sensor to monitor rivers of French Guiana subject to past or present small-scale gold mining activity.

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CONCLUSIONS GÉNÉRALES ET PERSPECTIVES

Face à l'évidence que la planète s'enfonce dans une nouvelle ère sous l'effet des « changements globaux», la communauté scientifique et les décideurs politiques en charge de la gestion des milieux aquatiques se sont lancés dans de vastes programmes de recherche. Pour cela, la Communauté Européenne s'est dotée de deux outils « Cadres » que sont les Programmes Cadre de Recherche et de Développement Technologique (PCRDT) d'une part et la Directive Cadre sur l'eau (DCE) d'autre part. L'aboutissement des activités de Recherche consistant aux transferts des connaissances acquises de la recherche d'investigation vers le développement technologique ou l'innovation puis vers l'application, la finalité de ces outils « Cadres » devient alors leur jonction.

Les travaux présentés dans cette thèse apportent des exemples concrets du potentiel de transfert des connaissances en écologie aquatique de la recherche exploratoire vers les domaines de « l'appliqué ». La figure 1, schématisant l'architecture de la thèse reprend les principaux résultats et perspectives détaillés ci-après.

Le « changement global » a été abordé par deux de ses composantes, à savoir le changement climatique et l'influence de l'occupation des sols (O.S.). L'approche de cette dernière a également donné lieu à une seconde dichotomie ; le changement d'échelle spatiale a été abordé ainsi que l'effet de l'altération des sols à travers la problématique de l'orpaillage en Guyane.

1. Le changement climatique

1.1. Principaux résultats

L'analyse des séries temporelles des relevés physico-chimiques des eaux des rivières du bassin Adour-Garonne, détaillée dans le premier chapitre, a mis en avant une tendance nette au réchauffement des eaux. En effet, parmi l'ensemble des dix-neuf paramètres suivis, les changements les plus forts concernent la température. Plus de la moitié des sites étudiés est concernée par ce changement. Au cours des trois décennies, la période 1984-1994 semble avoir été celle où les changements ont été les plus marqués. Nous notons que cette tendance est bien visible sur le continuum de la Garonne et moins discernable au niveau des cours d'eau secondaires. Les sites les moins impactés sont les sites dits « extrêmes » localisés en altitude dans les têtes de bassin.

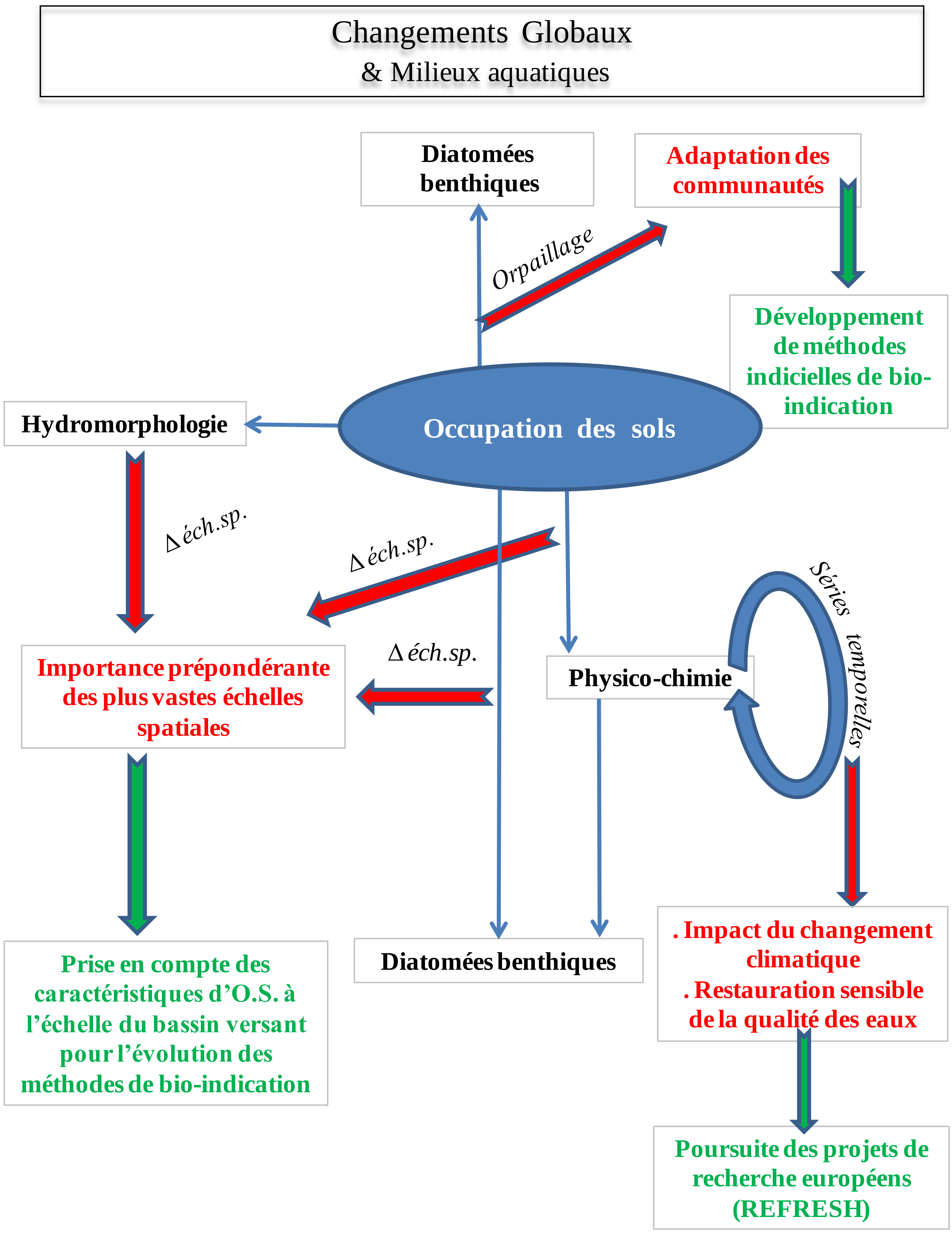


Figure 1 *: Représentation schématique des différents thèmes abordés (flèches bleu), des principaux résultats (flèches et texte en rouge) ainsi que des perspectives envisagées (flèches et texte en vert).*

1.2. Perspectives de recherche

Aucune étude comparable portant sur les séries chimiques temporelles de plusieurs décennies n'a fait l'objet de publications. Par son originalité cette étude constitue une référence pour le suivi à long terme de la qualité des eaux du bassin Adour-Garonne. Par ailleurs, elle répond au premier objectif de la Directive Cadre Européenne sur l'eau qui est l'établissement des conditions de référence. La nuance avec la demande de la DCE réside dans le fait que le référentiel établi est de dimension temporelle. L'étape suivante consistera donc à intégrer les données de la dernière décennie (2005 - 2015) collant ainsi très bien avec la date butoir de la DCE de 2015.

La hausse des températures représente une composante importante du changement global dont l'effet sur les écosystèmes aquatiques reste difficile à estimer. Le suivi des paramètres physico-chimiques sur trois décennies a démontré que les secteurs de tête de bassin proches des conditions naturelles sont encore relativement épargnés par la hausse des températures et constituent de fait des « capteurs » pertinents. A ce titre, ces sites sont considérés comme référentiels par la DCE pour le suivi et l'évaluation des ajustements écologiques impactant les eaux douces. Globalement, sur l'ensemble des réseaux hydrographiques, nous pouvons nous attendre à ce que la hausse des températures entraîne une atténuation du gradient thermique fluvial accompagnée d'une homogénéisation abiotique et biotique du milieu.

La « température-dépendance » des processus écologiques constitue un déterminant majeur délicat à appréhender et à maitriser pour atteindre les objectifs de bon état écologique de la DCE. Il est fort envisageable que le paramètre « température » constitue l'élément déclassant vis-à-vis duquel toute réversibilité soit impossible ou peu probable. L'impact de la hausse des températures sur le fonctionnement des écosystèmes aquatiques suscite donc de la part de la communauté scientifique une grande attention. Tout particulièrement, un lien doit être tiré entre l'organisation structurelle et fonctionnelle des biocénoses et la température. Ce volet est un des enjeux majeurs du projet européen REFRESH ($7^{ème}$ PCRDT - Adaptative Strategies to Mitigate the Impacts of Climate Change on European Freshwater Ecosystems) faisant suite au projet Européen Eurolimpacs. Un des principaux objectifs consiste à évaluer l'effet de l'ombrage (effet des zones forestières couvertes en comparaison aux zones agricoles ouvertes) sur l'évolution spatiale et temporelle de la température de l'eau, sur la structure des communautés de diatomées benthiques et de macro-invertébrés le long du gradient amont-aval. L'ambition du projet est d'extrapoler les résultats obtenus aux effets du changement climatique et de proposer des mesures d'atténuation des effets de la hausse des températures.

2. Influence de l'occupation des sols

2.1. Résultats relatifs à l'importance des échelles spatiales

Les facteurs du paysage influencent les écosystèmes aquatiques à travers un large panel d'échelles spatiales, la difficulté réside alors à déterminer quelle est l'importance relative de chacune d'entre elles et qu'elle est celle dont l'influence est la plus déterminante sur les diverses composantes du milieu.

Les chapitres deux et trois se sont focalisés sur cette problématique en utilisant une approche méthodologique similaire par découpage de l'occupation des sols selon cinq emprises spatiales différentes (depuis l'échelle locale de quelques centaines de mètres jusqu'à la prise en compte de la totalité du bassin versant). Des relations ont été établies entre chacun des patrons d'O.S. et différentes composantes abiotiques et biotiques des écosystèmes aquatiques : l'hydromorphologie, la physico-chimie et les communautés de diatomées benthiques.

Qu'il s'agisse des caractéristiques hydromorphologiques, physico-chimiques ou diatomiques, les traitements statistiques portés sur les bases de données ont fait ressortir trois résultats majeurs récurrents :

1) les relations les plus fortes avec les patrons d'O.S. ont été extraites pour l'emprise spatiale la plus vaste, à savoir celle du bassin versant pris dans son intégralité ;

2) la force des relations établies entres les métriques observées localement et les différentes échelles spatiales d'O.S. se structurent le long du gradient longitudinal amont-aval

3) à l'échelle du bassin versant, occupation des sols, physico-chimie et diatomées sont imbriquées dans une relation graduelle nommée «effet cascade». Cependant, pour chacune des métriques mise en relation, des nuances sont à apporter.

C'est avec les données d'hydromorphologie que les résultats ont été les plus tempérés. Il a été démontré tout particulièrement que l'influence les échelles spatiales d'O.S. variait en fonction de la localisation géographique des sites. Il s'est avéré que l'éloignement des têtes de bassin s'accompagnait de l'influence croissante des échelles les plus larges d'O.S. Parallèlement, dans les sites localisés dans les secteurs amonts, la dépendance établie entre les caractéristiques hydromorphologiques et les patrons d'O.S. est la même quelle que soit l'échelle spatiale considérée.

. Les liens établis entre la physico-chimie et les caractéristiques d'O.S. sont en adéquation avec le concept du continuum fluvial. En effet, plus l'échelle spatiale d'O.S. est vaste et plus la relation avec la physico-chimie est forte, appuyant, de fait, la notion de gradient longitudinal et d'effets cumulatifs.

. Concernant les diatomées benthiques, les résultats obtenus sont en concordance avec ceux de la physico-chimie, à la nuance près que la force des relations est toujours plus faible. Parallèlement, il a été montré que les diatomées et la physico-chimie sont étroitement liées, et que cette relation reste plus forte que celle établie par les diatomées avec l'O.S. Ces résultats ont donc souligné la hiérarchie des relations entre O.S., physico-chimie et diatomées. La force des relations est la plus élevée pour les connexions directes (O.S./chimie et chimie/diatomées) que pour les connections indirectes (O.S./diatomées). Les communautés de diatomées répondent par des connexions indirectes à l'O.S. à travers ses effets sur la qualité chimique de l'eau.

2.2. Effet du changement de l'occupation des sols sur la qualité chimique des eaux en Adour-Garonne

Cet aspect a été appréhendé indirectement *via* l'analyse des séries temporelles de la physico-chimie. En plus des informations relatives au changement climatique décrites ci-dessus, les résultats obtenus ont mis en évidence les changements significatifs affectant la chimie des eaux du bassin Adour-Garonne. Il apparait depuis cette dernière décennie une tendance à la diminution de l'eutrophisation. De nombreux sites ont montré une réduction des charges en azote et en phosphore durant la période 1995-2004. Les sites qui n'ont montré que très peu de changements au cours de ces trois dernières décennies sont les sites « extrêmes » de têtes de bassin, des zones estuariennes mais également les sites les plus fortement contaminés. Cette tendance à l'amélioration de la qualité de l'eau peut s'expliquer par i) une gestion plus efficace des pollutions diffuses due aux changements des pratiques agricoles, ii) un meilleur contrôle des rejets ponctuels urbains et/ou industriels et iii) le résultat des efforts d'épuration des eaux.

2.3. Prise en compte de l'occupation des sols dans le développement d'outils de bio-indication

Les deux études portant sur la variation de l'échelle spatiale de l'occupation des sols ont montré l'importance prépondérante de l'emprise spatiale la plus vaste. Dans le contexte de stations d'étude éloignées des sources de pollutions ponctuelles, les relations sont fortes entre les caractéristiques de l'O.S. à l'échelle du bassin versant, la qualité chimique et les communautés de diatomées benthiques.

Les méthodes actuelles de bio-indication par les assemblages de diatomées benthiques reposent sur la sensibilité des espèces vis-à-vis de la chimie. L'estimation de la qualité de l'eau est alors établie sur la base de valeurs indicielles (indice diatomique) qui traduisent de façon implicite les conditions environnementales du bassin versant. La qualité de l'eau intègre, sous une même appréciation, les conditions naturelles et les altérations d'origines anthropiques, englobant elles-mêmes les pollutions diffuses et les rejets ponctuels. Pour la mise au point de méthodes biologiques d'évaluation de la qualité des eaux, l'enjeu consiste à faire la part entre chacun de ces éléments. Concernant la distinction entre l'influence des conditions naturelles versus les conditions d'altération du milieu, cette problématique a été récemment traitée et a trouvé sa solution dans la mise au point des « Ecological Quality Ratio » (EQR). Cette méthode est une réponse à la DCE demandant aux États membres de définir les conditions de référence. L'évaluation de la qualité biologique de l'eau qui s'en suit consiste alors à déterminer l'écart entre les conditions théoriques de référence et une situation mesurée. Les EQR constituent donc une appréciation de ce que devrait être l'état d'un milieu dans les conditions naturelles.

Or, les caractéristiques d'occupation des sols représentent non seulement une source majeure d'altération des conditions environnementales mais également la seule base de données consistante permettant d'évaluer les pressions potentielles du paysage sur les eaux douces. La non prise-en-compte des caractéristiques de l'O.S. constitue à l'heure actuelle une lacune majeure des méthodes indicielles existantes. Il parait donc évident que la prochaine étape de l'évolution des méthodes de bio-indication prendra en compte directement ces données disponibles. Il serait alors envisageable de définir un indice, le pendant des EQR, évaluant la pression potentielle du paysage (« Landscape Pressure Ratio ! »).

La seconde difficulté des méthodes indicielles réside dans leur incapacité à faire la part entre pollution diffuse et rejets ponctuels. L'exploitation des patrons d'occupation des sols semble être le passage nécessaire pour appréhender cette problématique. Alors qu'il semble délicat d'établir une distinction entre les deux sources de pollution (diffuse ou ponctuelle) à partir d'une station de mesures prise isolément, une approche envisageable consisterait à étudier des portions de linéaires de cours d'eau délimités par deux stations de mesure où sont effectués des inventaires diatomiques. Ainsi entre deux points, les différences des valeurs indicielles pourraient être mises en parallèle avec l'O.S. entre ces deux points (pression du paysage). Ainsi à chaque station pourraient être associées des métriques diatomiques (valeur indicielle au niveau de la station, écart entre les deux stations) et des métriques du paysage (pression du paysage à l'échelle du bassin et pression du paysage entre les deux points d'étude).

2.4. Impact de l'orpaillage sur les communautés de diatomées benthiques des petits cours d'eau de Guyane

En Guyane, l'analyse de l'effet de l'altération des sols s'est portée sur la réponse des communautés de diatomées benthiques face aux conditions de stress dues à l'orpaillage. En forêt, l'extraction de l'or se fait à proximité des cours d'eau par lessivage intensif des sols. En plus de la déforestation, ce procédé entraine un rejet massif de sédiments fins dans le cours d'eau induisant une hausse de la turbidité, un colmatage du lit, ainsi que le rejet d'hydrocarbures et de métaux lourds. L'étude comparative des diatomées échantillonnées dans des cours d'eau différemment impactés (sites de référence sans orpaillage, sites avec orpaillage en cours et sites dont l'exploitation est arrêtée depuis au moins un an) a montré que les diatomées persistaient dans le milieu malgré des conditions de stress extrême, et présentaient des assemblages différents selon le niveau de perturbation. Il a été établi un lien entre l'intensité de l'orpaillage et les changements des assemblages diatomiques affectant à la fois leur structure taxonomique et fonctionnelle. Une relation directe a été mise en évidence entre la turbidité (et l'intensité de sédimentation) et la capacité motrice des diatomées. Parallèlement, aucun impact n'a été détecté sur les diatomées quant à un effet du rejet de métaux lourds. De nombreuses études ont montré que sous la contrainte d'un apport significatif de métaux lourds, les valves de diatomées présentent des anomalies de leur ornementation et des déformations marquées de leur contour, or rien de ceci n'a été observé dans les échantillons.

2.5. Perspectives de recherche en réponse à la problématique « Orpaillage »

Les résultats ont montré que les diatomées répondaient aux conditions de stress dues à l'orpaillage. De fait, les assemblages diatomiques apparaissent comme étant des capteurs pertinents pour assurer la surveillance des rivières de Guyane soumises aux activités d'orpaillage passées ou présentes. Il est alors concevable de développer un indice diatomique générique destiné à évaluer ce type de contrainte environnementale. Les détails ci-après apportent des éléments de réflexion quant au développement d'un tel outil.

L'identification taxonomique au genre s'est révélée suffisante pour percevoir un effet de l'orpaillage sur les communautés de diatomées. Tout particulièrement, les capacités de déplacement des diatomées se sont révélées être d'une importance capitale. Or, les distinctions taxonomiques permettant d'identifier les genres reposent essentiellement sur les critères qui déterminent les capacités motrices des diatomées, à savoir :

- la présence ou non d'un système raphéen,
- la course du raphé,
- la symétrie des valves

De ces critères deux dichotomies apparaissent (figure 2) :

- la première, portant sur « les formes de vie » différencie les diatomées fixées (épontiques) des formes libres (benthiques), sur base de la présence ou non d'un raphé et de systèmes de fixation au substrat ;
- la seconde, à partir des formes mobiles permet d'établir une classification des capacités motrices sur la base du degré de complexité du système raphéen.

Il est alors envisageable de quantifier le degré d'altération du milieu *via* le ratio « abondance relative des formes mobiles *versus* formes immobiles ». Plus ce ratio est élevé est plus le degré d'altération est marqué. En complément, la prise en compte des capacités motrices des assemblages apporte une indication quant à la dynamique d'altération.

La figure 3 illustre l'information qui peut être extraite en termes de bio-indication à partir des capacités de mobilité de genres significatifs de diatomées benthiques.

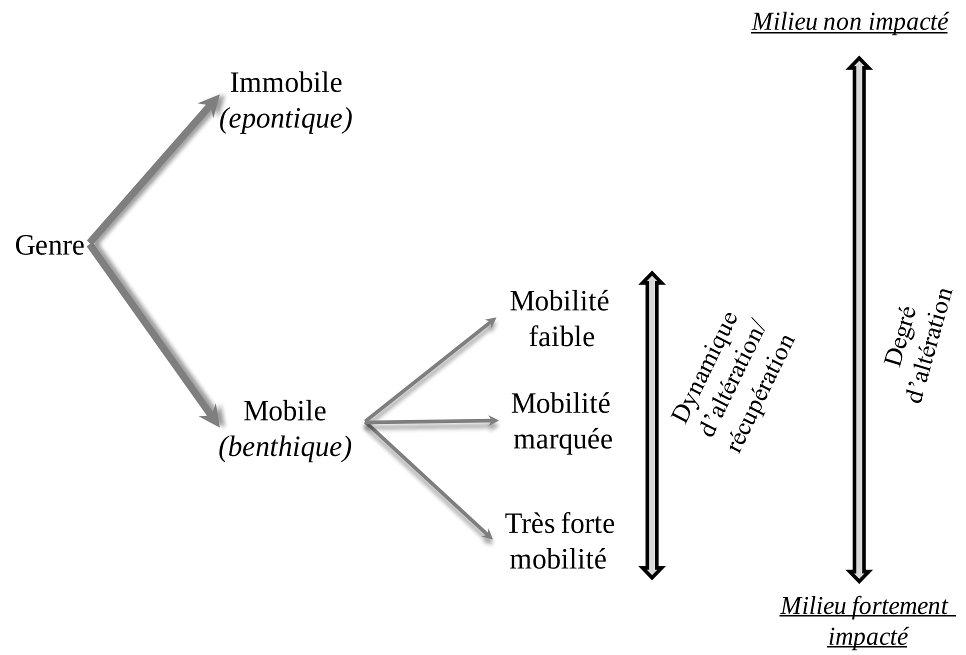


Figure 2*. Prise en compte des « formes de vie » et des capacités motrices des diatomées pour la mise au point d'un indice diatomique générique de sédimentation adapté aux contraintes d'orpaillage.*

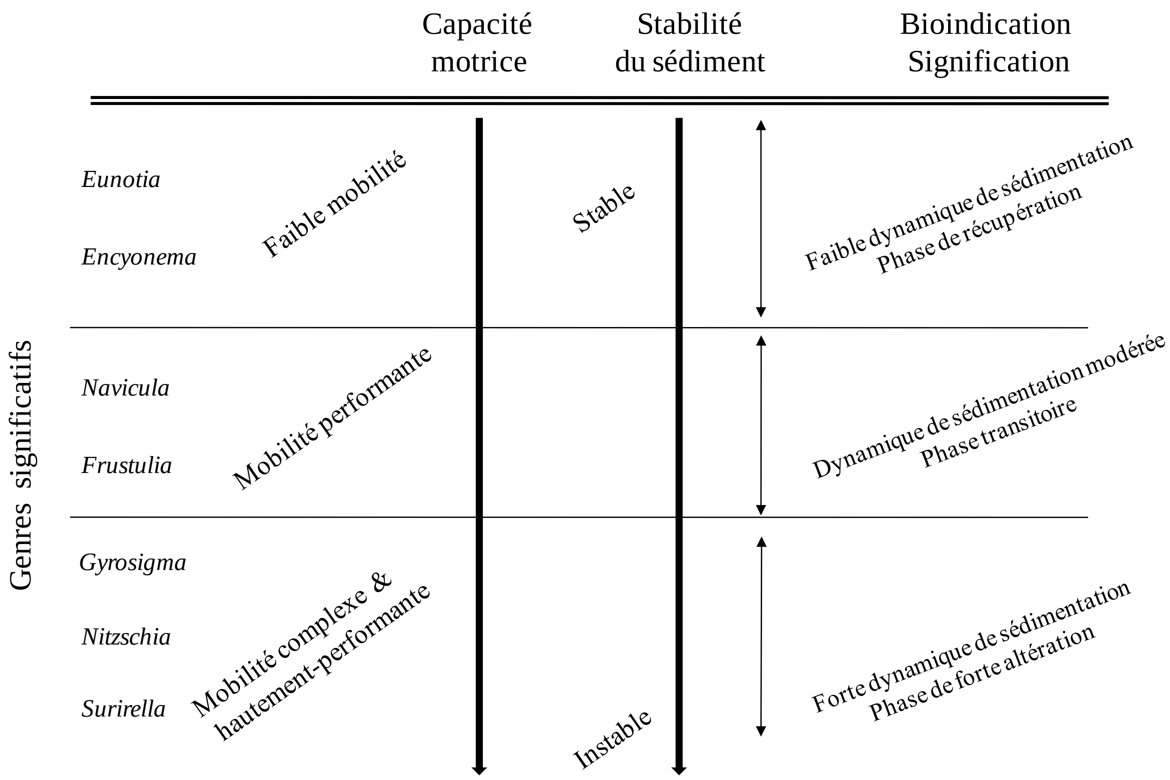


Figure 3*. Proposition d'une trame destinée à évaluer la dynamique de sédimentation et les processus de récupération du milieu sur la base des capacités motrices des diatomées benthiques.*

La mise au point d'un tel indice permettrait de s'affranchir des contraintes d'identification des diatomées au niveau spécifique impossible à réaliser dans l'état actuel des connaissances* et d'être de fait, un indice rapidement applicable par des « non spécialistes ». Il est également possible de couvrir un spectre plus large d'altérations en couplant un tel indice de sédimentation à des métriques de perturbation par les métaux lourds (par exemple en prenant en compte l'abondance des formes tératologiques).
(* en annexe « tentative » d'identification à l'espèce des diatomées échantillonnées dans deux stations de cours d'eau de la réserve des Nouragues).

3. Conclusion générale

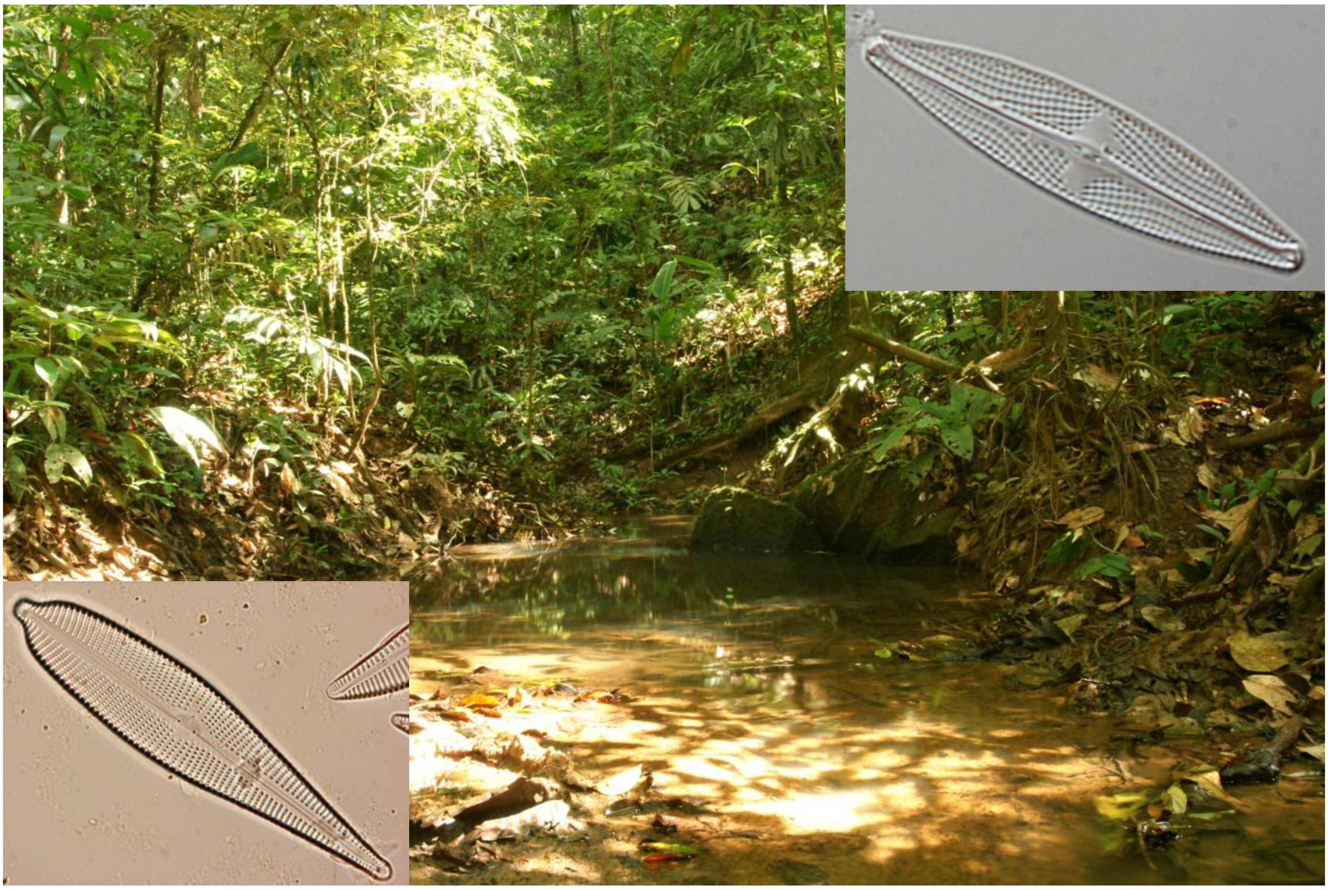
L'analyse exploratoire des bases de données d'occupation des sols, physico-chimiques, hydromorphologiques diatomiques dans les cours d'eau du bassin Adour-Garonne et diatomiques en Guyane a mis en évidence :

1) l'effet du changement global sur la qualité des eaux marqué par la hausse des températures et une atténuation sensible de l'eutrophisation ;
2) l'importance prépondérante de la prise en compte des patrons d'occupation des sols à l'échelle du bassin versant. A cette échelle, l'occupation des sols, la physico-chimie et les diatomées sont imbriquées dans une relation graduelle nommée «effet cascade»
3) la persistance des diatomées et le changement des caractéristiques des communautés périphytiques face aux conditions de stress extrême dues à l'orpaillage.

Ces résultats ont démontré leurs potentiels quant au transfert des connaissances vers le domaine de « l'appliqué », particulièrement en proposant :

1) un référentiel temporel de la qualité chimique des eaux du bassin Adour-Garonne servant d'appui au suivi à long terme de la qualité de l'eau, tel qu'il est demandé par la Directive Cadre Européenne sur l'eau ;
2) l'intégration des patrons de l'occupation des sols à l'échelle du bassin versant dans de nouveaux outils de bio-indication afin d'évaluer i) les pressions potentielles du paysage sur les milieux aquatiques et ii) d'identifier la part prise par la pollution diffuse de celle résultant de pollutions ponctuelles ;
3) la mise au point d'un nouvel indice diatomique générique basé sur les capacités motrices des diatomées.

ANNEXES



1. Codification Corine land cover 2000

2. Planches iconographiques - diatomées de cours d’eau de Guyane

Nomenclature Corine land cover 2000 (Chapitre 2 et 3)

Code	Label Level3 - CLC3	Label Level2 - CLC2	Label Level1 - CLC1
111	Continuous urban fabric	Urban fabric	Artificial surfaces
112	Discontinuous urban fabric		
121	Industrial or commercial units	Industrial, commercial and transport units	
122	Road and rail networks and associated land		
123	Port areas		
124	Airports		
131	Mineral extraction sites	Mine, dump and construction sites	
132	Dump sites		
133	Construction sites		
141	Green urban areas	Artificial, non-agricultural vegetated areas	
142	Sport and leisure facilities		
211	Non-irrigated arable land	Arable land	Agricultural areas
212	Permanently irrigated land		
213	Rice fields		
221	Vineyards	Permanent crops	
222	Fruit trees and berry plantations		
223	Olive groves		
231	Pastures	Pastures	
241	Annual crops associated with permanent crops	Heterogeneous agricultural areas	
242	Complex cultivation patterns		
243	Land principally occupied by agriculture, with significant areas of natural vegetation		
244	Agro-forestry areas		
311	Broad-leaved forest	Forests	Forest and semi natural areas
312	Coniferous forest		
313	Mixed forest		
321	Natural grasslands	Scrub and/or herbaceous vegetation associations	
322	Moors and heathland		
323	Sclerophyllous vegetation		
324	Transitional woodland-shrub		
331	Beaches, dunes, sands	Open spaces with little or no vegetation	
332	Bare rocks		
333	Sparsely vegetated areas		
334	Burnt areas		
335	Glaciers and perpetual snow		
411	Inland marshes	Inland wetlands	Wetlands
412	Peat bogs		
421	Salt marshes	Maritime wetlands	
422	Salines		
423	Intertidal flats		
511	Water courses	Inland waters	Water bodies
512	Water bodies		
521	Coastal lagoons	Marine waters	
522	Estuaries		
523	Sea and ocean		

Identifications et illustrations iconographiques des diatomées de deux sites d'études de la Réserve des Nouragues (Guyane française) : 1) Crique petite Nouragues (site de référence R1) ; 2) Crique Japigny (site avec orpaillage en cours, C1)

Planche I Crique Petites Nouragues - épilithon en faciès lotique M.O. x2000

Figs 1 - 21.	*Nupela praecipua* (Reichardt) Reichardt
Fig. 22.	*Achnanthidium exiguum* var. *constrictum* (Grunow) Andresen, Stoermer & Kreis
Figs 23 - 24.	*Cocconeis* spec. cf. *pseudolineata* (Geitler) Lange-Bertalot
Fig. 25.	*Cocconeis* spec. cf *disculoides* Hustedt
Fig. 26	*Eunotia* spec.
Figs 27-29.	*Eunotia* spec. cf *exsecta* (Cleve-Euler) Nörpel-Schempp & Lange-Bertalot
Fig. 30.	*Eunotia* spec.
Fig. 31.	*Geissleria neotropica* Metzeltin & Lange-Bertalot
Figs 32-35.	*Diadesmis biceps* Arnott
Fig. 36.	*Navicula rivulorum* Lange-Bertalot & Rumrich
Fig. 37 a,b.	*Navicula(dicta) seminulum* (Grunow) Lange-Bertalot
Fig. 38,39.	*Gomphonema brasiliensoide* Metzeltin, Lange-Bertalot & García-Rodríguez
Fig. 40.	*Gomphonema* spec.

Figs 1a,b, 5a,b, 7a,b. Frustules complets. Figs 3a,b, 24a,b, 25a,b, 27a,b, 31a,b, 36a,b, 37a,b. Variations de mise au point. Figs 20, 21, 26, 27a,b, 38. Vues connectives.

Planche II Crique Petites Nouragues - épilithon en faciès lotique M.O. x2000

Figs 1a-c.	*Gomphonema* spec.
Fig. 2.	*Gomphonema* spec.
Figs 3-13.	*Gomphosphenia* spec. cf. *lingulatiformis* (Lange-Bertalot & Reichardt) Lange-Bertalot

Fig. 14. *Gomphonema* spec.

Fig. 15. *Navicula longicephala* Hustedt var. *longicephala*

Fig. 16. *Navicula quasidisjuncta* Lange-Bertalot & Rumrich

Fig. 17. *Caloneis* spec.

Fig. 18. *Navicula viridulacalcis* var. *viridulacalcis* Lange-Bertalot

Figs 19-21. *Navicula jacobii* Manguin

Fig. 22. *Navicula cryptocephala* Kützing

Figs. 23-26. *Nitzschia amphibia* Grunow f. *amphibia*

Fig. 27. *Nitzschia fonticola* Grunow

Fig. 28. *Surirella* spec.

Figs 1, 2, 10-14, 23,24. Vues connectives. Figs 1a-c, 24a,b, 26a,b. Variations de mise au point.

Planche III Crique Japigny - épilithon en faciès lotique M.O. x2000

Fig. 1. *Aulacoseira granulata* (Ehrenberg) Simonsen

Figs 2-6. *Fragilaria bidens* Heiberg

Figs 7, 8. *Eunotia* spec.

Fig. 9. *Eunotia* spec.

Fig. 10. *Eunotia botuliformis* Wild, Nörpel & Lange-Bertalot

Fig. 11. *Eunotia meridiana* Metzeltin & Lange-Bertalot

Figs 12, 13 (?) *Eunotia luna* var. *aequalis* Hustedt

Fig. 14. *Eunotia camelus* Ehrenberg

Figs 15-24. *Achnanthidium macrocephalum* (Hustedt) Round & Bukhtiyarova

Fig. 25. *Chamaepinnularia brasilianopsis* Metzeltin & Lange-Bertalot

Fig. 26-27. *Chamaepinnularia brasiliana* Metzeltin & Lange-Bertalot

Fig. 28. *Chamaepinnularia* spec.

Figs. 29,30. *Navicula longicephala* Hustedt var. *longicephala*

Figs 7a,b, 8a-c. Vues connectives. Figs 7a,b, 8a-c, 17a,b. Variations de mise au point sur le même frustule.

Planche IV Crique Japigny - épilithon en faciès lotique M.O. x2000

Figs 1-9. *Navicula coraliana* Metzeltin & Lange-Bertalot

Figs 10-20. *Navicula* spec. cf. *exilis* Kützing

Figs 4a,b. Variations de mise au point.

Planche V Crique Japigny - épilithon en faciès lotique M.O. x2000

Figs 1-5. *Navicula* spec. cf. *cryptocephala* Kützing

Figs 6, 7. *Frustulia weinholdii* Hustedt

Fig. 8. *Frustulia saxonica* Rabenhorst

Fig. 9a,b. *Frustulia neofrenguellii* Lange-Bertalot & Rumrich

Fig. 10. *Frustulia* spec.

Figs 5a,b, 9a,b. Variations de mise au point.

Planche VI Crique Japigny - épilithon en faciès lotique M.O. x2000

Figs 1-12. *Frustulia saxoneotropica* Metzeltin & Lange-Bertalot

Figs 3a,b. Variations de mise au point.

Planche VII Crique Japigny - épilithon en faciès lotique M.O. x2000

Figs 1-8. *Brachysira neoexilis* Lange-Bertalot

Figs 9-14. *Gyrosigma reimeri* Sterrenburg

Figs 1a,b, 4a,b, 8a,b. Variations de mise au point sur le même frustule. Fig. 2. Vue connective.

Planche VIII Crique Japigny - épilithon en faciès lotique M.O. x2000

Figs 1-6. *Encyonema neogracile* var. *tenuipunctata* Krammer & Lange-Bertalot

Figs 7-8. *Encyonema incurvatum* Krammer

Fig. 9. *Encyonema subminutum* Krammer & Lange-Bertalot

Fig. 10. *Encyonema ponteanum* Krammer

Figs 11-14(?) *Gomphonema lagenula* Kützing

Fig. 15. *Gomphonema* spec.

Fig. 16. *Gomphonema* spec. cf. *tenuissimum* Fricke

Figs 17-18. *Nitzschia palea* (Kützing) W. Smith var. *debilis* (Kützing) Grunow

Fig. 19. *Nitzschia dissipata* (Kützing) Grunow var. *dissipata*

Fig. 20. *Nitzschia* spec.

Figs 21-29. *Surirella tenuissima* Hustedt

Figs 28a,b. Variations de mise au point. Figs. 15, 28. Vues connectives.

Planche I

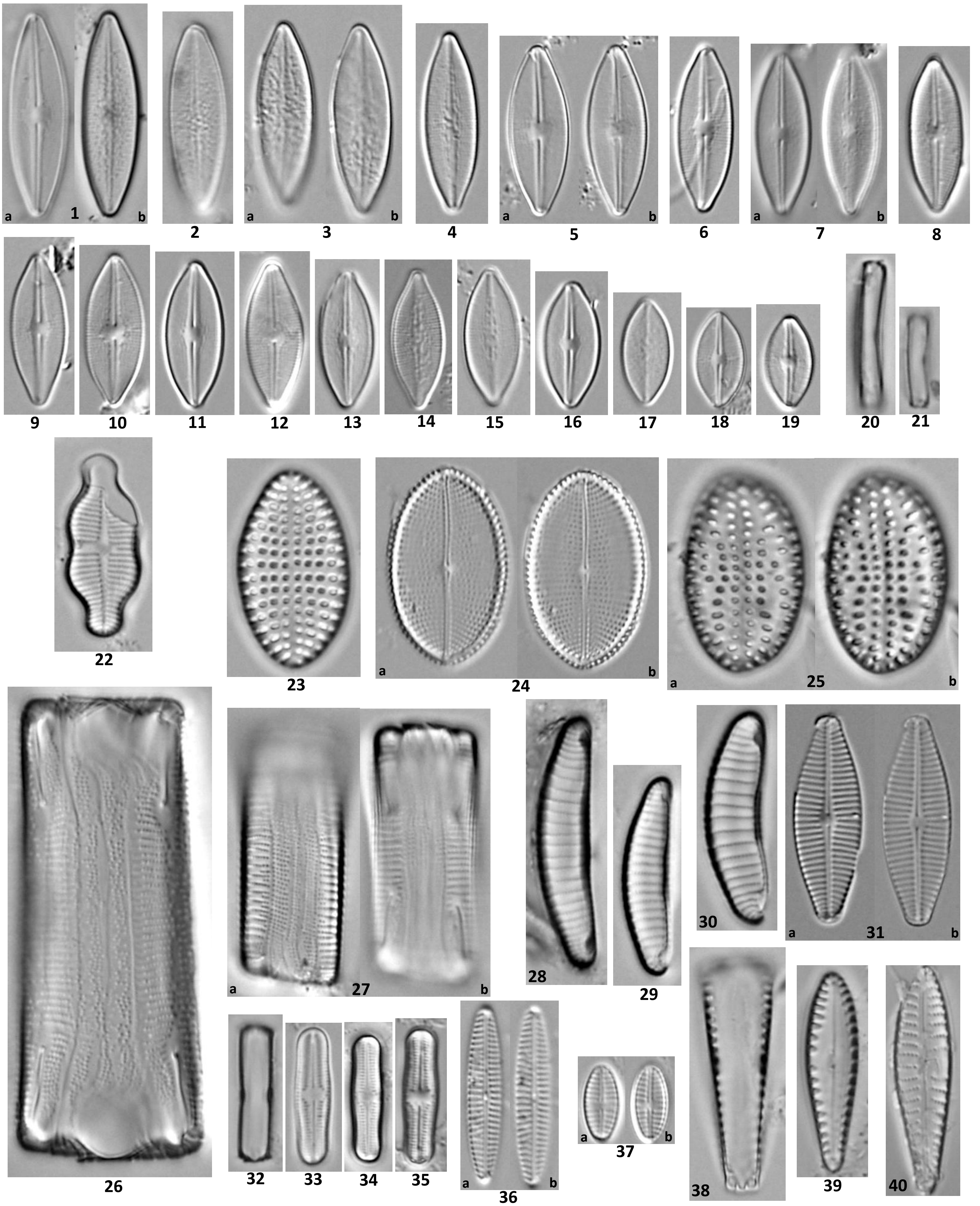

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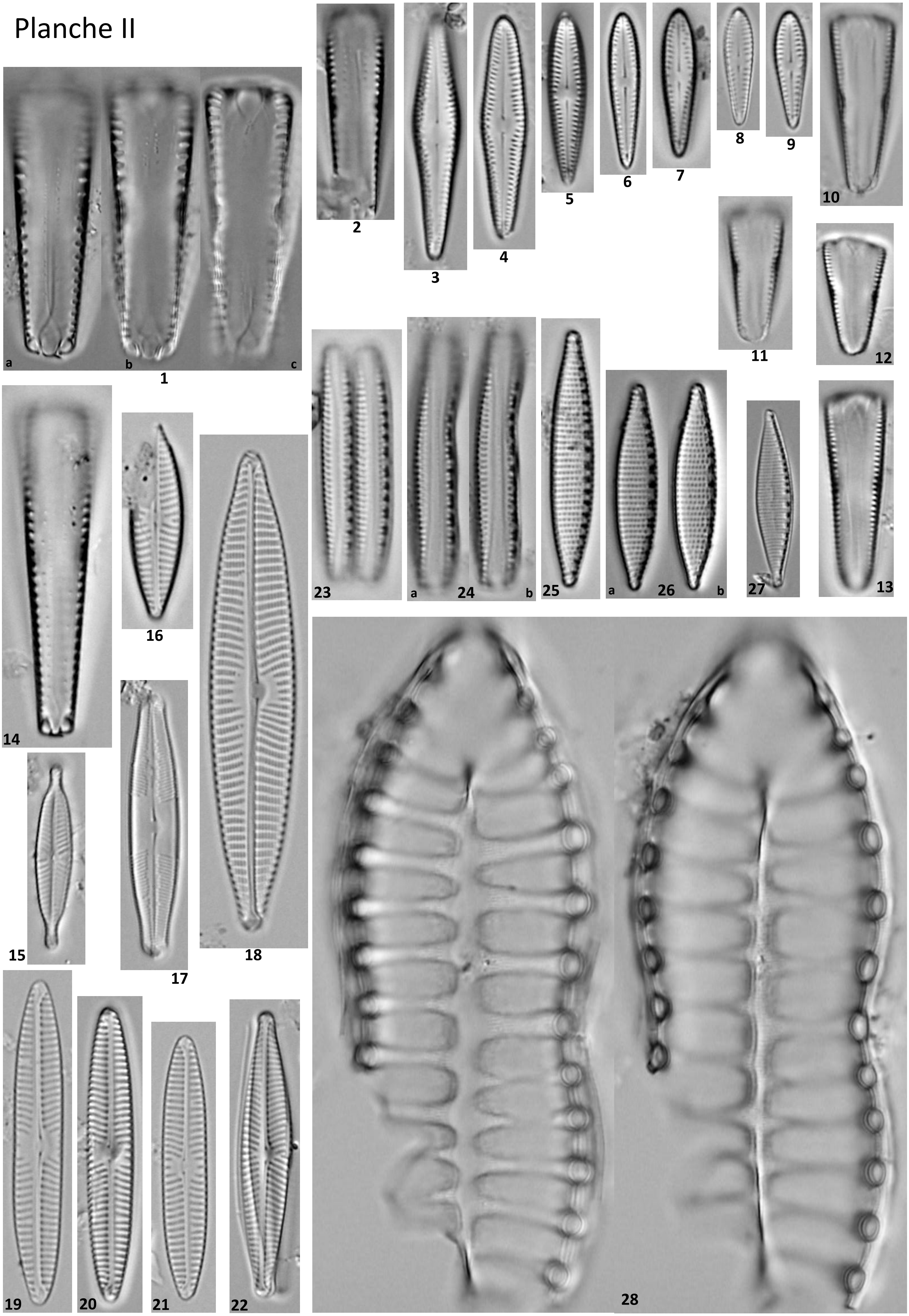
Planche II



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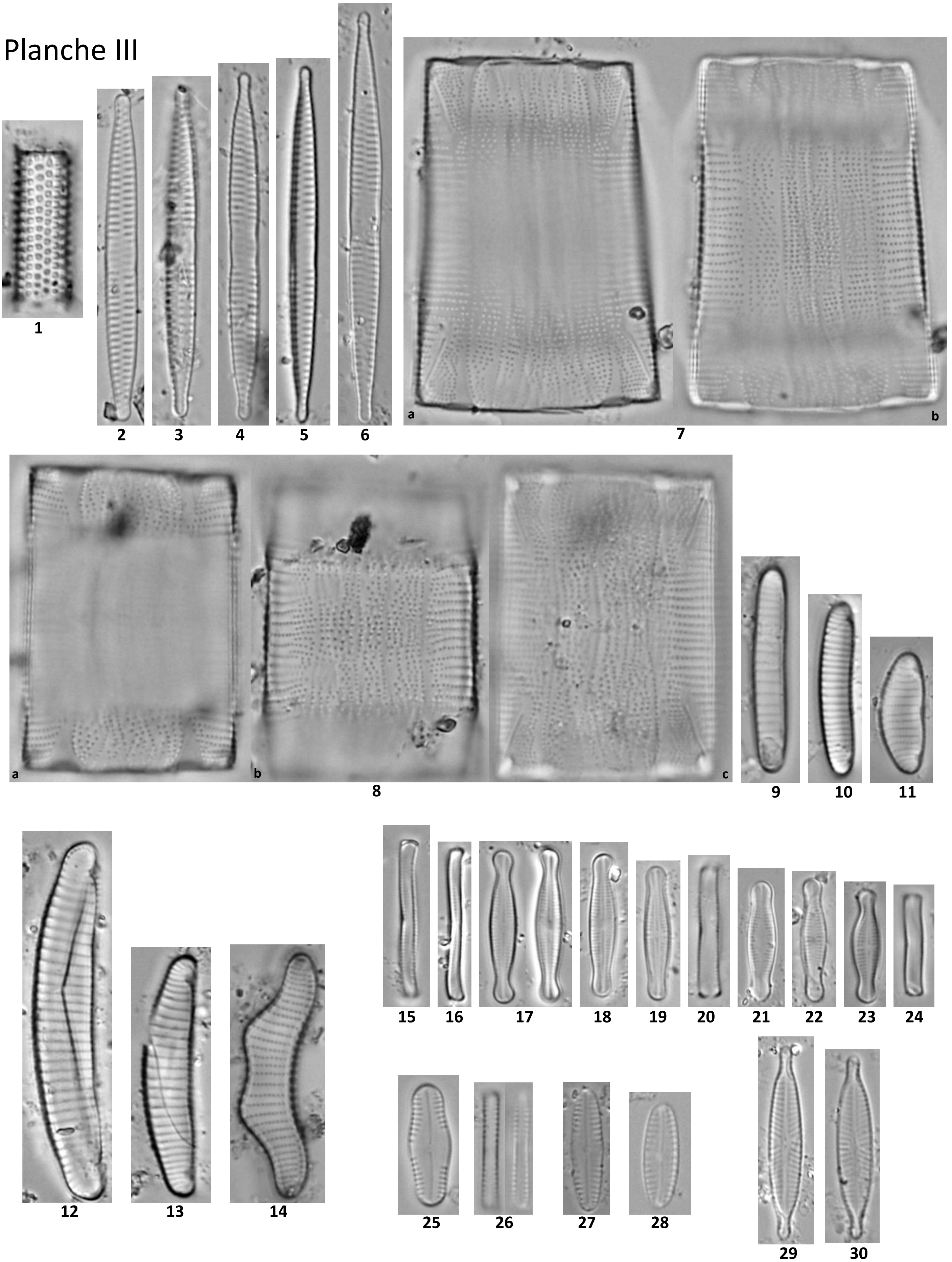
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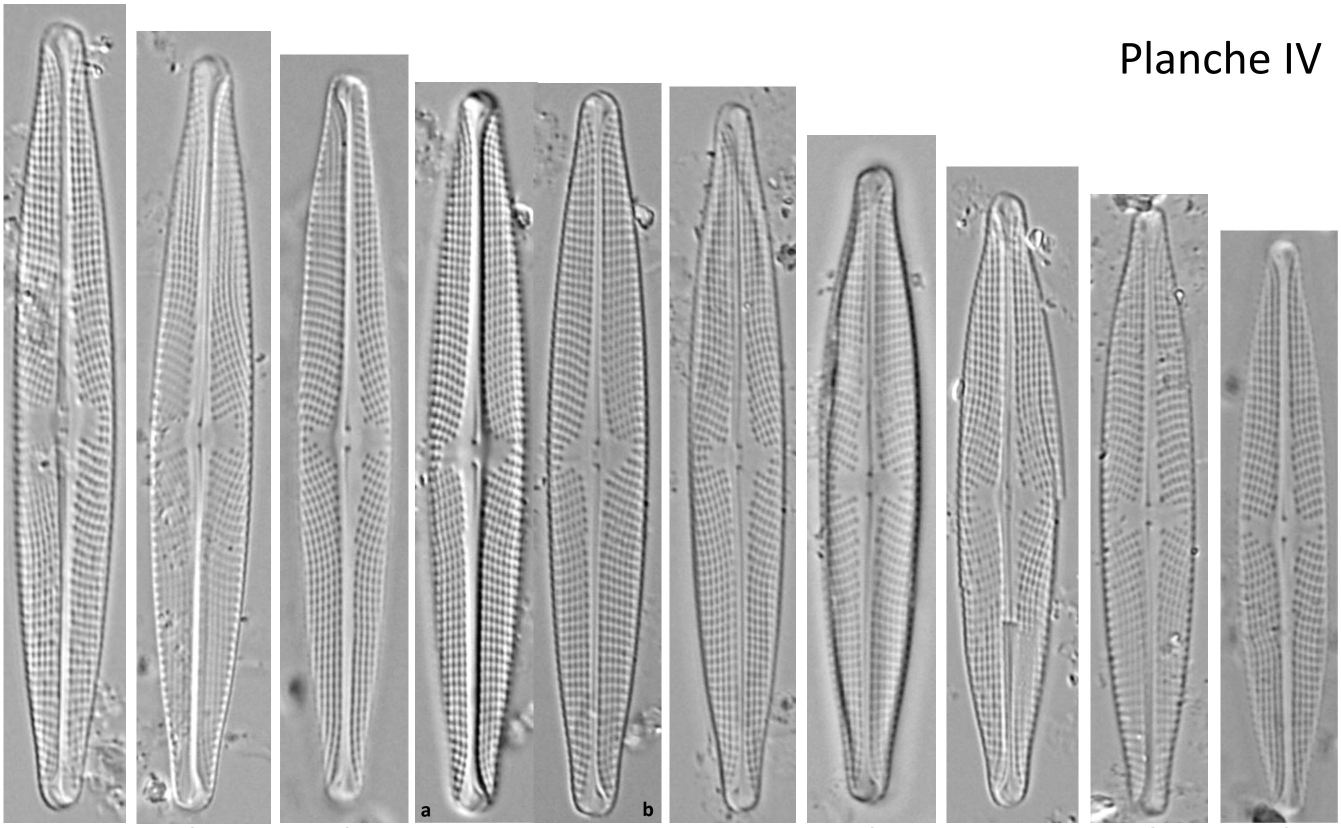
Planche IV



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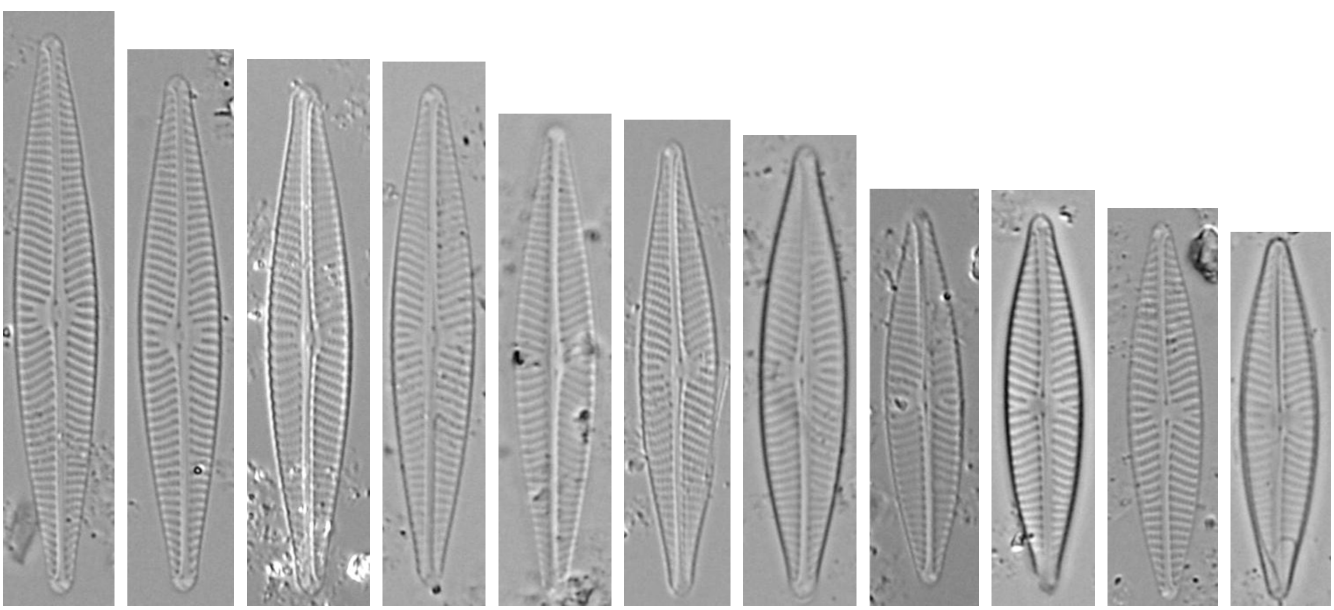

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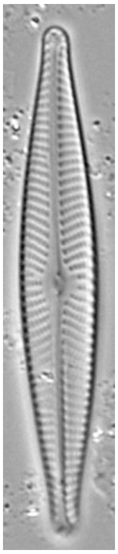
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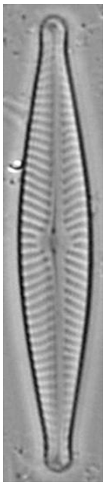
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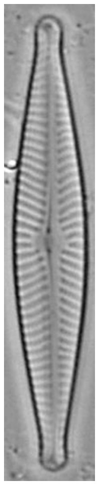
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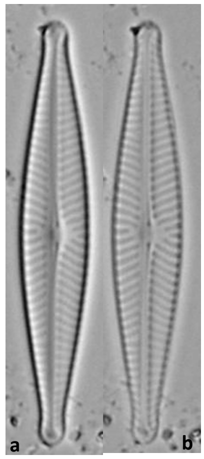

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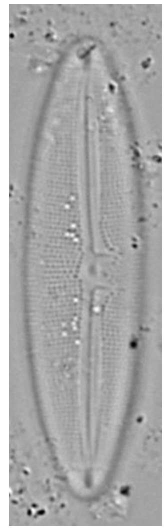
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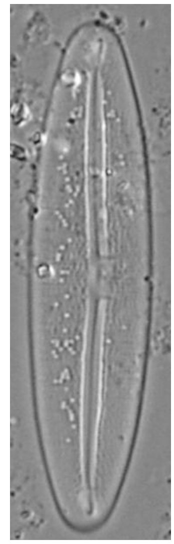
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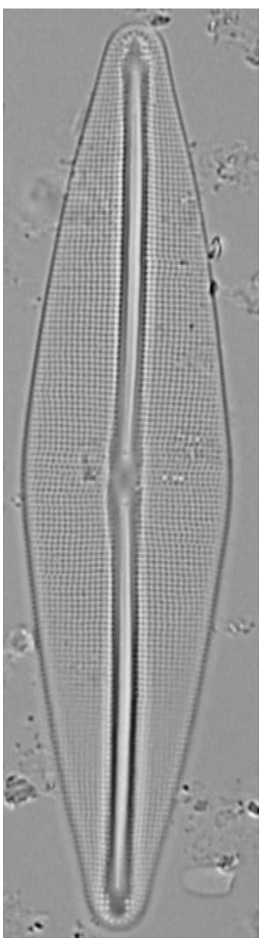
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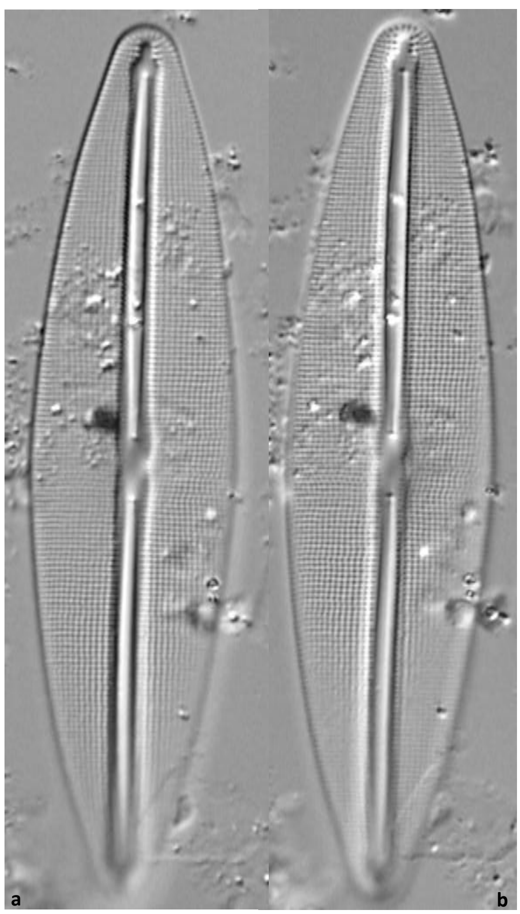

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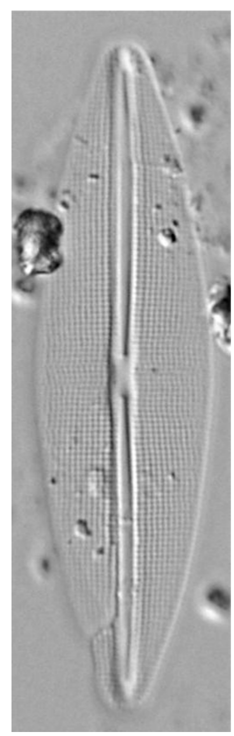
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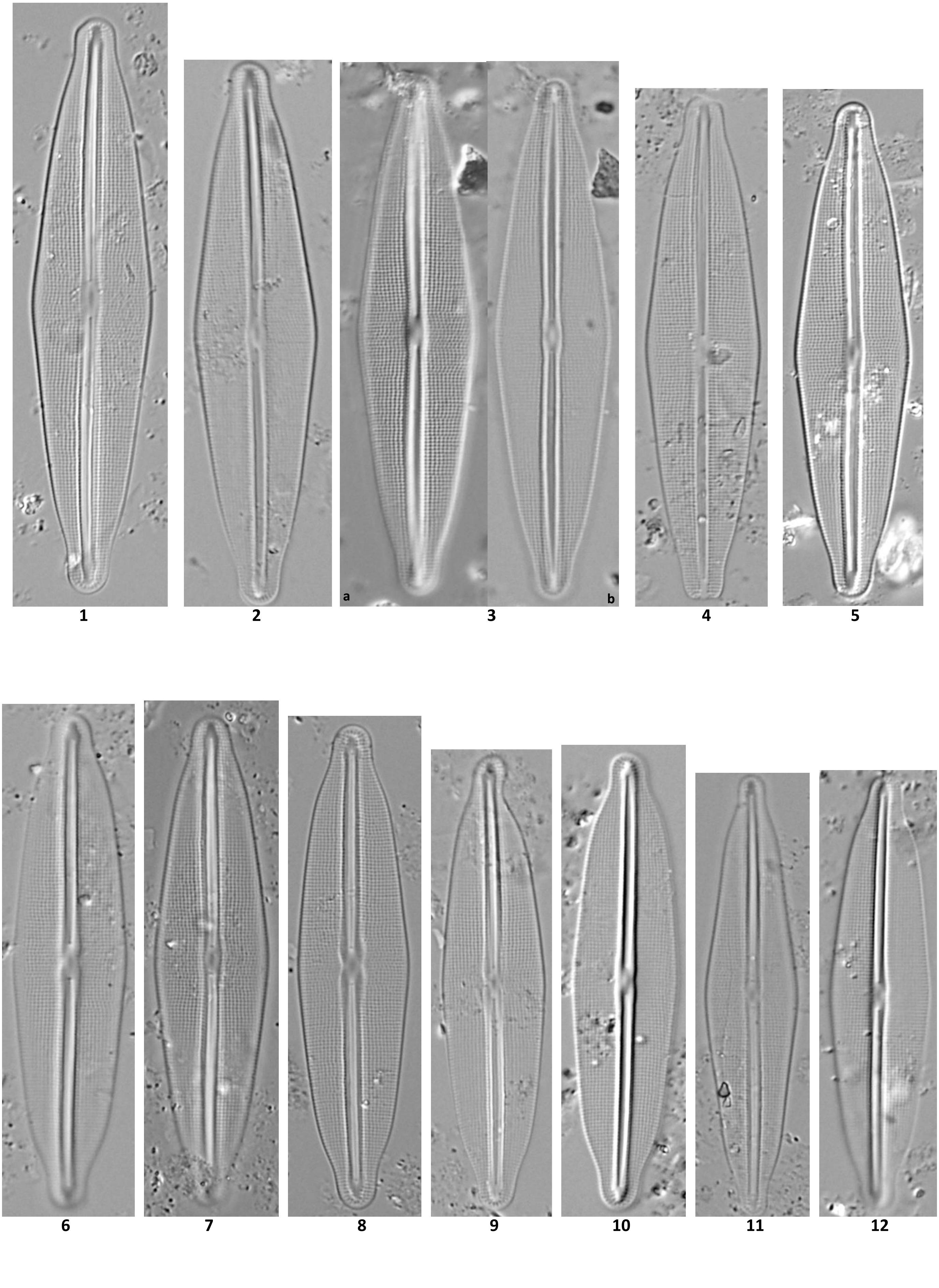

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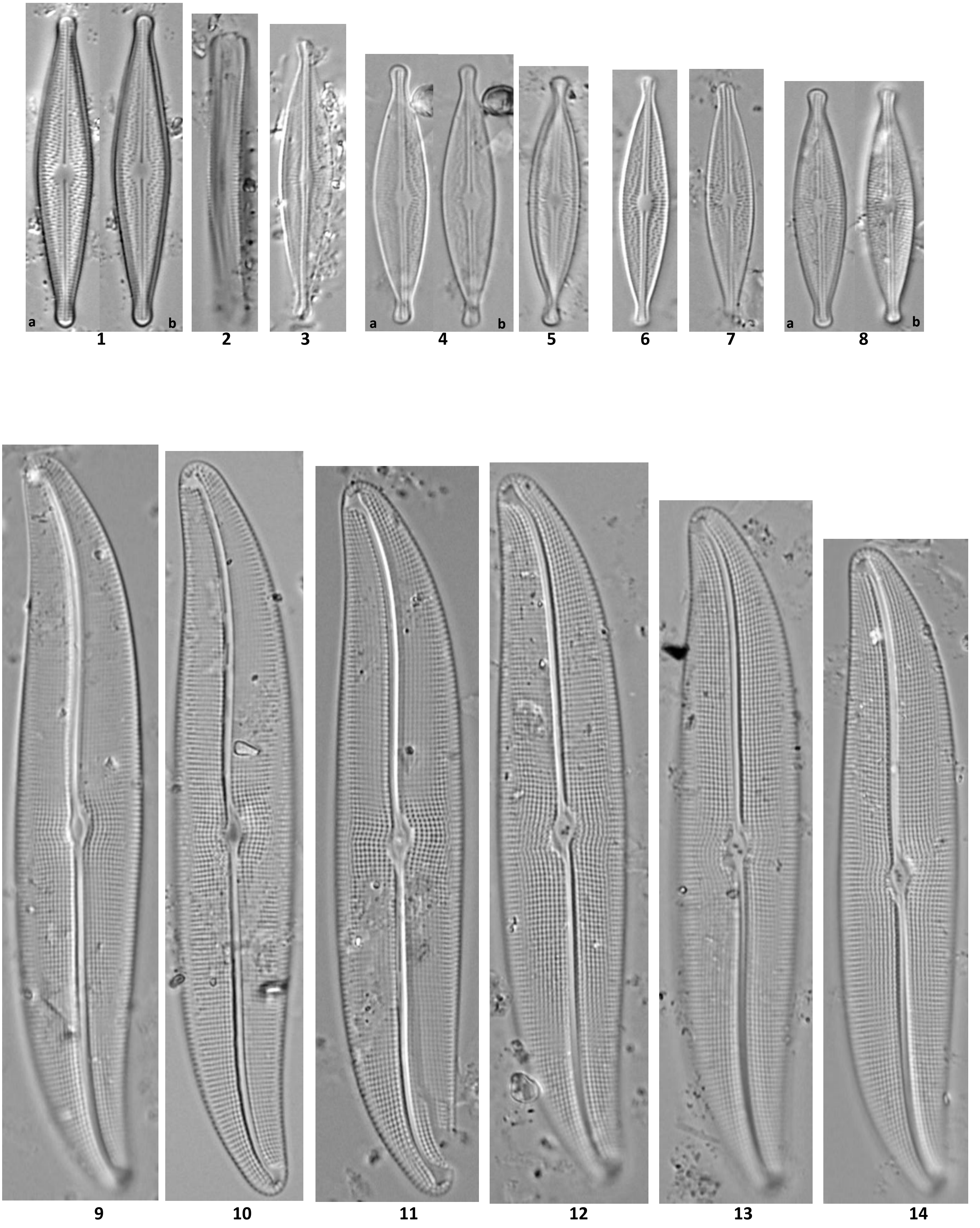

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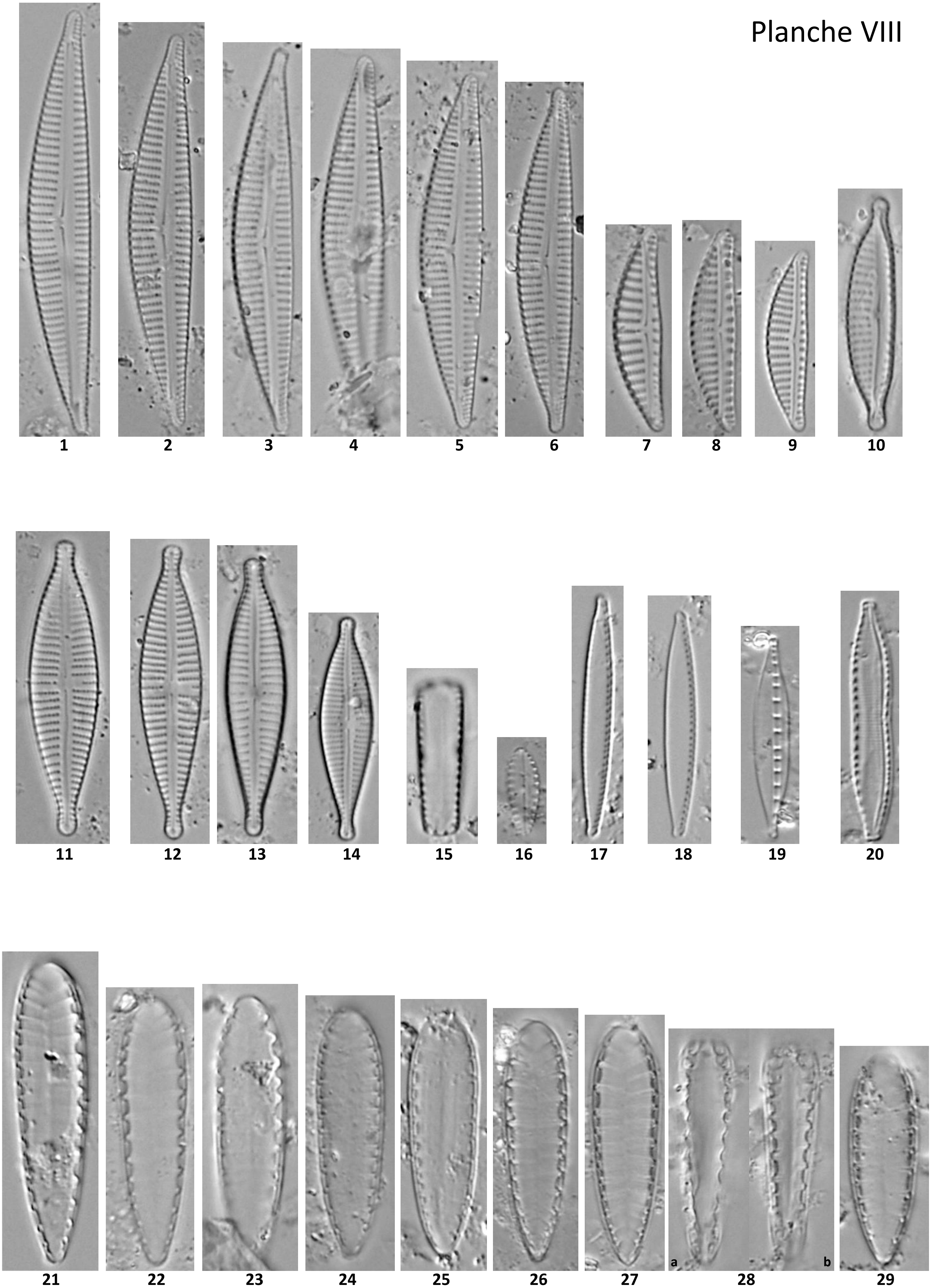

AUTHOR: Loïc Tudesque

TITLE: Temporal and Spatial Analyses of Chemical, Hydromorphological and Diatom Metrics related to Global Changes.

DIRECTORS: Michel Coste, Sovan Lek

ABSTRACT:

This thesis aimed at assessing the effect of global changes on aquatic ecosystems. The exploratory analysis of the land cover patterns, physicochemical, hydromorphological, and diatom databases in the Adour-Garonne basin and the diatom flora of streams in French Guyana highlighted:

1) the effect of the global changes on the water quality characterized by the temperature increase and the significant mitigation of eutrophication ;

2) the strongest influence of the land cover patterns at the catchment scale ;

3) the persistence of the diatom flora and the change of community structures facing extreme stress due to gold mining ;

These results testified their importance as for their potential transfers towards the fields of “applied research”, particularly proposing:

1) a temporal reference frame of the chemical water quality of the Adour-Garonne basin ;

2) to integrate the land cover patterns extracted at the catchment scale in order to improve or develop new biomonitoring tools ;

3) the development of a new generic diatom index appropriate to the French Guyana context based on the diatom motility abilities.

KEYWORDS : artificial neural networks ; biomonitoring ; diatom ; French Guiana ; freshwater ; Garonne ; hydromorphology ; land cover ; model of long-term change ; life-form ; mining ; motility ; random forests ; recovery ; spatial scale ; STATIS ; stream ; time series ; turbidity ; Water quality.

LABORATORY : Laboratoire Evolution & Diversité Biologique (EDB - UMR 5174), Université Paul Sabatier, 118 route de Narbonne, Bât. 4R3, 31062 Toulouse cedex 9, France

AUTEUR: Loïc Tudesque

TITRE: Analyse Temporelle et Spatiale des Composantes Chimiques, Hydromorphologiques et Diatomiques en Relation avec les Changements Globaux.

DIRECTEURS DE THÈSE: Michel Coste, Sovan Lek

RÉSUMÉ:

L'objectif de cette thèse était d'évaluer l'effet des changements globaux sur les milieux aquatiques. L'analyse exploratoire des bases de données d'occupation des sols, de physico-chimie, d'hydromorphologie, de diatomées dans les cours d'eau du bassin Adour-Garonne et de diatomées en Guyane a mis en évidence :

1) l'effet du changement global sur la qualité des eaux marquée par la hausse des températures et une atténuation sensible de l'eutrophisation ;

2) l'importance prépondérante des patrons d'occupation des sols à l'échelle du bassin versant ;

3) la persistance des diatomées et le changement des caractéristiques des communautés périphytiques face aux conditions de stress extrême dues à l'orpaillage en Guyane.

Ces résultats ont démontré leurs valeurs quant à leurs potentiels de transfert vers les domaines de «la recherche appliquée» en proposant :

1) un référentiel temporel de la qualité chimique des eaux du bassin Adour-Garonne ;

2) l'intégration des patrons de l'occupation des sols à l'échelle du bassin versant dans le développement de nouveaux outils de bio-indication ;

3) la mise au point d'un indice diatomique générique basé sur les capacités motrices des diatomées et destiné au contexte guyanais.

MOTS CLÉS : bio-indication ; diatomée ; eau douce ; échelle spatiale ; Garonne ; Guyane française ; hydromorphologie ; modèle de changement temporel ; mobilité ; occupation des sols ; orpaillage ; qualité d'eau ; random forests ; récupération ; réseaux de neurones artificiels ; ruisseau ; séries temporelles ; STATIS ; trait de vie ; turbidité.

LABORATOIRE : Laboratoire Evolution & Diversité Biologique (EDB – UMR 5174), Université Paul Sabatier, 118 route de Narbonne, Bât. 4R3, 31062 Toulouse cedex 9, France