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Comparison of statistical algorithms for detecting homogeneous river reaches along a longitudinal continuum VERSION ACCEPTEE 20 8 2011

Thierry Leviandier^{a,*}, A. Alber^b, F. Le Ber^c, H. Piégay^b

^a*ENGEEES 1 quai Koch BP 1039 F 67070 Strasbourg Cedex, France*

^b*University of Lyon, UMR 5600 CNRS, Site ENS Lyon, 15 Parvis R. Descartes, 69362 Lyon cedex 07, France*

^c*Laboratoire d'hydrologie et de géochimie . Université de Strasbourg, CNRS, ENGEEES 1 quai Koch BP 1039 F 67070 Strasbourg Cedex, France*

Abstract

Seven methods designed to delineate homogeneous river segments, belonging to four families, namely — tests of homogeneity, contrast enhancing, spatially constrained classification, and hidden Markov models — are compared, firstly on their principles, then on a case study, and on theoretical templates. These templates contain patterns found in the case study but not considered in the standard assumptions of statistical methods, such as gradients and curvilinear structures. The influence of data resolution, noise and weak satisfaction of the assumptions underlying the methods are investigated. The control of the number of reaches obtained in order to achieve meaningful comparisons is discussed. No method is found that outperforms all the others on all trials. However, the methods with sequential algorithms (keeping at order $n+1$ all breakpoints found at order n) fail more often than those running complete optimisation at any order. The Hubert-Kehagias method and Hidden Markov Models are the most successful at identifying subpatterns encapsulated within the templates. Ergodic Hidden Markov Models are, moreover, liable to exhibit transition areas.

Keywords: river segmentation; spatial organisation; GIS; river continuum

*corresponding author. Tel: 33 3 88 24 82 38; Fax: 33 3 88 24 82 84; E-mail:thierry.leviandier@engees.unistra.fr

1. Introduction

Since the pioneering work of Schumm (1977), a river channel has been considered a longitudinal continuum, its width or depth increasing downstream in response to discharge, whereas its slope and grain size decrease (Leopold and Maddock, 1953). In terms of hydraulic geometry, different authors, such as Hey (1982) and Ferguson (1986) have proposed regionally based empirical models, giving support to the ‘space-time substitution’ model used to highlight the channel’s responses to different anthropogenic pressures, such as urbanisation or channel straightening. These pressures disrupt the longitudinal trends of the width increase in downstream channel (Gregory and Chin, 2002). Following these studies, several authors stated discontinuities within the river continuum, notably in relation to the lithological settings (Ichim and Radoane, 1990; Ferguson and Ashworth, 1991; Piégay et al., 2000a), tectonics (Schumm and Spitz, 1996; Astrade and Bravard, 1999), hillslope processes (Grant et al., 1990), riparian vegetation (Clifton, 1989), hydraulic and sedimentary effects of confluences (Rice, 1999), or human infrastructures and sea level (Gurnell, 1997). Other authors underlined the effects of these physical discontinuities on the biocenotic conditions (Minshall and Petersen, 1985; Piégay et al., 2000b; Rice et al., 2001). Perry and Schaeffer (1987) then proposed the ‘discontinuum river concept’ in response to the so-called ‘river continuum concept’ of Vannote et al. (1980).

As a consequence, new research perspectives have been opened to reconsider the factors controlling the longitudinal discontinuities and to identify them along the continuum (Benda et al., 2004; Torgersen et al., 2008). Because rivers are hierarchically organised (Frissell et al., 1986), longitudinal discontinuities can be investigated for a range of spatial scales, from the habitat to the network scale. Following Frissell et al. (1986), we refer here to the segments and reaches scales, which are stretches of river with a well-identified geomorphic structure, in between the network scale and the habitat scale. Segments are considered portions of valleys with relatively clear boundaries controlled by geological settings or bounded by tributary junctions, whereas reaches are more closely associated with homogenous geomorphic patterns, also characterised by clear boundaries (e.g., meandering, braided, straight channels). The longitudinal structure studied here is very close to the temporal univariate series, the time line being replaced by a longitudinal line. Although the longitudinal periodicity of geomorphic structures has been quite well studied — as stated by Grant et al. (1990), Hardisty (1993), Madej

(1999), and Aubry and Piégay (2001) — the detection of thresholds and homogeneous reaches has not been sufficiently developed from a scientific point of view, being mainly subjectively based, and uses visual or graphic estimates (Astrade and Bravard, 1999; Gurnell et al., 2000; Michalková et al., 2011). The moving average method has been used to smooth the local variability to highlight major thresholds on a signal with higher frequency, but it may induce cyclic effects cumulating the successive random effects (Slutzky, 1937; Bernier, 1965). A cumulated frequency curve is also a graphic mean to show the unstationarity of a given univariate series visually. Empirically, fitting a linear trend and its confidence intervals to detect stationarity is possible (Brunet-Moret, 1971). Even if such a cumulated curve is not always easy to read, one or several trends and associated thresholds can then be highlighted. Most of the available tools used to characterise longitudinal fluvial patterns are therefore univariate, whereas the questions posed in this domain are often multivariate, which is also a key issue to consider. Indeed, the detection of homogeneous segments along rivers is now becoming a challenging perspective because of the GIS layers, digital elevation model (DEM), and remote sensing data available to study such problems at a regional scale and the needs of river managers to describe river systems at the basin scale (several thousand to several hundred thousand square kilometers) for planning and targeting their actions, as demonstrated by recent publications on this topic (Beechie et al., 2006; Brenden et al., 2008). The regionalisation of synthetic geomorphic indicators should highlight how the longitudinal features control the ecological potentials and contribute to the pressure-impact models. The aim of this contribution is therefore to inventory, describe, and compare a set of statistical methods that can be used to discretise a longitudinal continuum of a continuous variable (e.g., slope, width, depth) automatically. The hydrographic network is considered here a set of longitudinal segments/reaches separated by confluences with a focus on linear features that are disconnected hierarchically. Some of the statistical methods have already been used in such contexts, whereas others are applied to temporal series such as rainfall and discharge. The aim is therefore to assess the potentiality and the sensitivity of statistical methods according to different types of spatial distribution and resolution to detect their application domain. Section 2 presents four types of methods that are considered for comparison (seven methods with variants taken into account). The principles of algorithms are compared in section 3, and an empirical benchmark is performed in section 4. In the empirical part, the methodology, restricted to

76 the univariate case, is presented consisting of designing synthetic templates
77 and applying the algorithms in optimal and nonoptimal conditions on these
78 templates and on a case study. What is learned from the tests for applica-
79 tions is discussed in section 5 together with the limits and potential of the
80 univariate methodology.

81 2. Methods for delineation

82 Four types of methods are investigated, some of them with many variants,
83 others relatively specific.

- 84 • **Homogeneity test (HT)** methods consist of testing a null hypothe-
85 sis of the homogeneity of means. They have been mainly applied to
86 climatic and hydrological series usually to detect one threshold (some-
87 times based on the Bayesian approach) (Gardner Jr, 1969; Lee and
88 Heghinian, 1977; Buishand, 1982, 1984; Aka et al., 1996; Lubes-Niel
89 et al., 1998; Robson et al., 1998), sometimes several thresholds (Scheffe,
90 1959; Hubert, 1989, 2000). Others were developed for water quality sur-
91 veys (Hirsch et al., 1991). Single-threshold tests such as the Pettitt test
92 have also been applied to detect several thresholds (Alber and Piégay,
93 2010). Only two of these methods, the Pettitt and Hubert methods,
94 are described in detail here. One of the most commonly used is the
95 Pettitt test (Pettitt, 1979; Zhang et al., 2008).
- 96 • **Contrast-enhancing (CE)** methods share with the HT methods an up-
97 down approach to splitting, but explicitly assume heterogeneity. This
98 type is represented only by the contrast-enhancing clustering process,
99 proposed by Leviandier et al. (2000) and applied to the design of a
100 rainfall stochastic process. This method detects a rupture, not by the
101 optimisation of certain criteria, but by means of a ‘separation equation’
102 that yields a point satisfying certain relationships between the average
103 intensity of the variable and the length of the subinterval on the left-
104 and right-hand sides of the point. At least two types of separation
105 equations were found necessary; when the equations had no root on the
106 entire interval (no intersection of two curves), taking a point minimising
107 the distance between the two curves was proposed to avoid stopping
108 the procedure too early.

- 109 • **Spatially constrained clustering methods (SCC)** (Brenden et al.,
110 2008) are ordinary clustering methods, used in the particular case of
111 spatial objects, so that a new object in a class is preferentially ag-
112 gregated to classes to which nearby objects have already been aggre-
113 gated. The ultimate simplification of the procedure consists of deciding
114 whether a point belongs to a class on its left or on its right.
- 115 • **Hidden Markov Models (HMM s)** (Rabiner and Juang, 1986) are
116 rather different. They consider a stochastic process along the line and
117 a random variable at each point, which produces the observed value.
118 A reader familiar with the framework adapted to the other methods
119 would expect that the distribution of the random variable depends on
120 the ‘class’ to which the current point belongs. This is slightly more
121 complicated as each point is not conditioned by its belonging to a class
122 but by the pathway on which it has walked from the beginning of the
123 line by a succession of random transitions between a small number
124 of states. As at the end of a statistical fitting, many points have a
125 probability 1 of being in one state and adjacent points are in the same
126 state, it produces clusters similar to that of the other methods, with
127 the difference that some points remain conditioned by several states
128 with different probabilities between 0 and 1. This feature offers the
129 possibility of exhibiting transition areas.

130 Two methods are considered within the HT family, one of them with two
131 variants and two variants of the HMM method, which gives a total of seven
132 methods.

133 2.1. Details on HT

134 As these methods are based on statistical tests, the model contains a
135 parameter, namely the probability of a type I risk (risk of rejecting the ho-
136 mogeneity assumption even though it is true), which governs the detection
137 of a stepwise shift and the number of stepwise shifts if applied several times.
138 It must be noted that the detection of several shifts should be done with
139 generalised tests on means (Scheffe, 1959) that is not a simple iterated ap-
140 plication of the test for one shift. That simplification generally contains a
141 logical contradiction: a discontinuity is sought at iteration i in a segment
142 assumed to be homogeneous at iteration $i-1$.

2.1.1. Description of the Pettitt test

The sequence of random variables $X_1, X_2, \dots, X_n$ may have a change point. The question is to evaluate the probability that the following conditions are satisfied: the sequence of random variables $X_1, X_2, \dots, X_n$ has a change point at T if X_t for $t = 1, 2, \dots, T$ has a common distribution function $F_1(x)$, X_t for $t = T+1, \dots, n$ has a common distribution function $F_2(x)$ and $F_1(x) \neq F_2(x)$. The null hypothesis (H_0) is defined by the stationarity of the series, i.e. no change (or $T = n$). The H_0 is tested against the alternative hypothesis H_a defined by a change. Let t be the rank and K_n the nonparametric statistic:

$$K_n = \min_t \sum_{i=1}^t \sum_{j=t+1}^n \text{sign}(X_i - X_j) \quad (1)$$

with $\text{sign}(\theta) = 1$ if $\theta > 0$, 0 if $\theta = 0$, -1 if $\theta < 0$.

Let k be the value taken by K_n on the distribution. The significance probability p associated with k is determined approximately by

$$p \sim 2 \exp\left(\frac{-6k^2}{n^3 + n^2}\right) \quad (2)$$

If p is inferior to the risk α defined by the operator, then H_0 is rejected and a change point is localised at the rank d for which K_N occurs. The Pettitt test has been implemented to detect several change points in a given statistical distribution by running the algorithm iteratively. Considering a given initial distribution, it is stationary if no change point is detected for a given α risk. If a change point is detected, two new subseries are generated on each side of the change point, the latter being integrated into the downstream reach. The Pettitt test runs on subseries as long as change points are detected.

2.1.2. The Hubert method and its reformulation in dynamic programming

The principle of the Hubert method (Hubert, 1989, 2000) is to optimise the approximation of a one-dimensional function by a piecewise constant function under the constraint that two adjacent segments are significantly different. The method does not violate the assumptions of tests, though considering means pairwise may be seen as an approximation of the Scheffe test.

The Hubert method was initially proposed with an algorithm of low efficiency, unable to work on large datasets. Kehagias et al. (2005) noted that the problem could be written within the dynamic programming framework and therefore be solved with a fast-running algorithm. Though the optimum at

174 order $k + 1$ cannot be derived from the optimum at order k , the idea is that
 175 the solution at order $k + 1$, finishing at point t , can be written as a function
 176 of the set of solutions at order k , optimal on the length $[1, s]$ with $s < t$. Let
 177 p depend on k such that $[p, s]$ is the last segment in the optimal segmentation
 178 $S(k, s)$.

179 Let $c(s, t)$ be the cost of using the mean (or another function) instead of the
 180 observed values between points s and t and $C(k, s)$ the minimal cost at order
 181 k between 1 and s . Let v be the last point.

182 The Hubert method is reformulated in Eqs. (3) to (5):

$$q = \underset{s \in S}{Min} C(k, s) + c(s, t) \quad (3)$$

with S defined by significant changes in s and t in interval p, v

$$p(k + 1, t) = q \quad (4)$$

$$C(k + 1, t) = C(k, q) + c(q, t) \quad (5)$$

183 With appropriate initialisation, backtracking the optimal segmentation, and
 184 the rules to stop the procedure, the optimisation problem under the con-
 185 straints of significant changes is quickly solved by this system.

186 In this paper, the Fisher-Snedecor F function used for the test was calculated
 187 with the approximation of Li and Martin (2002) using the Fortran code of
 188 the Lahey Fortran library for the χ^2 function, owned by E.J. Szondi, whose
 189 source was Bargmann and Gosh (1963).

190 The proper application of the test depends on the length of the segments.
 191 We also tested the simplification using a threshold on the ratio of the sum of
 192 variances divided by the whole variance (of the segment under study); as it
 193 is independent of the length, the calculation is much faster. This simplifica-
 194 tion is not fully respectful of statistical theory and may produce a different
 195 delineation. It differs from the improvement of the algorithm proposed by
 196 Gedikli et al. (2010), which involves a reduction of the number of partitions
 197 explored.

198 2.2. Details on contrast enhancing

199 The idea was to design a simple stochastic model such that the location
 200 and the height of the step of a stepwise shift are defined together — requiring
 201 a unique random number in a Montecarlo simulation not used in this paper
 202 — . Let l_1 and l_2 be the average of the variable on each side of a point of
 203 abscissa i in a segment of length n , $t = i/n$ and $r_i = l_2/l_1$.

204 The separation algorithm used in this study seeks a breakpoint by the fol-
 205 lowing subalgorithms, in this order:

- 206 • $\max(r_i)$ under the condition that $r_i > 2$, with a constraint keeping
 207 from selecting successively two neighbouring points with this subalgo-
 208 rithm;
- 209 • separation equations $r_i = t^2, r_i = 2(1 - t)$ (the first one delivers the
 210 right location of a stepwise shift between two horizontal straight lines)
 211 and the same equations the other way round (from upstream); and
- 212 • $\min(|r_i - t^2|), \min(|r_i - 2(1 - t)|)$ and the same the other way round

213 The segmentation of previously found segments is prioritised according to
 214 values of the function $n^\alpha l^\beta \sigma^\gamma$, σ being the variance within the segment.
 215 In the first applications to rainfall-runoff modeling, it was important to give
 216 some weight to the volume, thus to parameters α, β ; but in the geomorpho-
 217 logical application, these parameters are $\alpha = \beta = 0; \gamma = 1$ to put emphasis
 218 on the variance σ .

219 2.3. Details on SCC

220 The VAST method (valley segment affinity search technique) shares with
 221 its parent method CAST (cluster affinity search technique) its ‘intent to
 222 partition a set of n objects into K groups such that objects within groups are
 223 more similar than objects in different groups’ (Brenden et al. (2008) quoting
 224 Ben-Dor et al. (1999)). The algorithm uses an affinity threshold value: the
 225 larger the threshold value is, the larger (and fewer) the groups are. The
 226 VAST program (Brenden et al., 2008) includes several possibilities for the
 227 measurement of affinity and other options, but only the first one prompted
 228 by the program was used.

229 2.4. Hidden Markov models

230 The Hidden Markov models are capable of segmenting a data sequence in
 231 stationary and transient parts and to building up a classification of the data
 232 together with the *a posteriori* probability of this classification. In an HMM,
 233 there is a double stochastic process (Baker, 1974):

- 234 • **the former** (a probability density function) is hidden from the observer
 235 and is defined on a sequence of states (a Markov chain);

- **the latter** is visible — it produces an observation at each slot t depending on the probability density function that is defined on the state in which the Markov chain stays at t .

Kehagias (2004) has proposed using first-order hidden Markov models (HMM1) for hydrological and environmental time series. In this paper, a second-order hidden Markov model (HMM2) was used, where the underlying state sequence is a second-order Markov chain. Therefore, the probability of a transition between two states at point t depends on the states in which the process was at point $t - 1$ and $t - 2$. Thus, an HMM2 is specified by

- **a set of N states** called $S = \{s_1, \dots, s_N\}$;
- **a three-dimensional matrix** (a_{ijk}) over S^3 :

$$\begin{aligned} a_{ijk} &= \text{Prob}(q_t = s_k / q_{t-1} = s_j, q_{t-2} = s_i) \\ &= \text{Prob}(q_t = s_k / q_{t-1} = s_j, q_{t-2} = s_i, q_{t-3} = \dots) \end{aligned} \quad (6)$$

with the constraints $\sum_{k=1}^N a_{ijk} = 1$, $\forall (i, j) \in [1, N]^2$ and where q_t is the current state at point t ; and

- **a set of N discrete distributions:** $b_i(\cdot)$ is the distribution of observations associated with the state s_i ; this distribution may be parametric, nonparametric or even given by an HMM (Mari and Le Ber, 2006).

An HMM1 is usually estimated by the Baum-Welch algorithm, which is related to the EM algorithm (Dempster et al., 1977). Mari et al. (1997) have shown that an HMM2 can be estimated in the same way. The estimation is an iterative process starting with an initial model and a corpus of sequences of observations that the HMM2 must fit. Usually, the initial model has equiprobable transition probabilities and a uniform distribution in each state. At each step, the Baum-Welch algorithm determines a new model in which the likelihood of the sequences of observation increases. Hence this estimation process converges to a local maximum, according to the maximum likelihood (ML) estimation criteria (Dempster et al., 1977; Mari and Schott, 2001; Mari et al., 1997). The Kullback-Leibler distance between the distributions associated with the states (Tou and Gonzales, 1974) was used to assess the final model. Two states that are too close are merged and the resulting model is retrained.

266 In order to describe directional processes as time series (here longitudinal
 267 series), mainly linear (or left-to-right) HMM models are used. In these models,
 268 once the state has been visited, it cannot be reached again. In other words,
 269 the transition probability between state i and state j , a_{ij} , is set to 0 if $i > j$.
 270 On the contrary, in ergodic models all the transitions, retrotransitions (from
 271 $i + 1$ to i), as well as distant transitions (between i and $i + 2$, $i + 3$, etc.,
 272 are authorised (Fig. 1). Such models are used, for instance, to analyse agri-
 273 cultural or genomic data. Indeed, they reveal repetitive patterns, such as
 274 crop rotations or protein promoters (Le Ber et al., 2006; Eng et al., 2009).
 275 This can also be interesting for detecting similar (characterised by the same
 276 distribution) but distant river segments or reaches; therefore both linear and
 277 ergodic models are considered in the following, written respectively 1HMM and
 278 eHMM.

Fig. 1

279 3. Comparing the principles of the methods

280 3.1. Algorithms

281 All methods considered perform clustering, contrary to another type of
 282 classification methods that tries to recognise predefined patterns. They dif-
 283 fer mainly in their focus on aggregating or disaggregating. The HMM method
 284 is somewhat different, as it works with a fixed number of states equivalent
 285 to clusters throughout the procedure, though it is always possible to resume
 286 the procedure with another number or to merge clusters. The methods are
 287 described according to five functions usually performed by subalgorithms
 288 (Table 1). Since these methods are not necessarily dedicated only to per-
 289 form delineation, some features related to their potential to deliver other
 290 information will be discussed below. These subalgorithms are:

- 291 • **Separation:** How does the method decide there is a discontinuity, or
 292 in the HMM method, a more or less steep change?
- 293 • **(Retro)propagation:** Once a new step has been found, is there a
 294 correction of reaches found before?
- 295 • **Merging:** Is there a procedure for merging two adjacent reaches after
 296 they have been modified if they have become too similar?
- 297 • **Stopping:** What is the criterion to stop the procedure at an acceptable
 298 (or significant from a statistical standpoint) level?

Table 1: Comparison of methods according to embedded algorithms

	Heterogeneity tests (HT) (Pettitt, Hubert)	Contrast enhancing (CE)	Spatial constraint clustering (SCC)	Hidden Markov Model (HMM)
Separation	Extremum of statistical criterion	Separation equation	Similarity criterion	Likelihood maximum on the entire data set
(Retro)-propagation	No	Possible generalisation	Yes	
Merging	No	Possible generalisation	Similarity criterion	Similarity criterion
Stopping or control of output resolution	Statistical risk or predefinite max. size	Predefinite max. size or failure of separation	Criterion based on intra- and inter-variances or threshold on similarity	Maximum number of iterations
Prioritisation	Same as for separation (error minimisation in Hubert method)	Extremum on subintervals of a statistical criterion	Many variants	Irrelevant

299 • **Prioritisation:** When the procedure has been performed up to some
 300 order, what criterion should be used to choose the next reach to be
 301 tested for splitting (irrelevant for the **HMM** method)?

302 Table 1 presents a synthesis of the methods characterised by the subalgo-
 303 rithms embedded. Complementary comments are given hereafter.

304 • **The column on HT methods** is divided into two, because of the al-
 305 ternative of stopping either on the number of reaches or on a statistical
 306 test.

307 • **The column for the HMM method** has a two-line cell and a cell la-
 308 belled irrelevant, which confirms that the method is atypical.

309 • **(Retro)propagation and merging** were attributed to **CE** methods
 310 but not to **HT** methods. It would be contradictory to the principle,
 311 though it would be possible to do so for any method. For the **CE**
 312 method, it seems more acceptable; but in this case, with the loss of
 313 the separation equations, the possibility of a stochastic model of sub-
 314 intervals built only on the separation points is also lost (because the
 315 variable under study is no longer determined by the points of separa-
 316 tion).

317 3.2. Other features

318 3.2.1. Parameterisation

319 The methods under study have generally one or several parameters, mainly
 320 in the stopping criterion, which controls the result and particularly the num-
 321 ber of reaches found. This will be discussed in the empirical comparison,
 322 section 4.4.

323 3.2.2. Multidimensional extension

324 The longitudinal approach is often associated with geomorphic typolo-
 325 gies. As shown by previous authors (Mosley, 1987; Schmitt et al., 2007),
 326 geomorphic typology is based on a set of variables to try to summarise the
 327 complexity, often based on exploratory multivariate statistics. Gurnell (1997)
 328 studied the hydraulic thresholds along a fluvial continuum using a discrim-
 329 inating factorial analysis to test whether a statistical difference is observed
 330 among four reaches initially distinguished according to a set of criteria such
 331 as specific limits (the tidal influence, infrastructures) but also geomorphic

characteristic (mean depth, mean width, wetted section). It may therefore be interesting to directly segment a river using several variables rather than to combine independent delineations or to modify a univariate one in a second step. Though a benchmark of the methods on multidimension variables is not within the scope of this paper, their potential for generalisation must not be overlooked. The HT methods, based on statistical tests on one-dimensional distributions, are the most difficult to generalise. In the CE method, the equations of separation are clearly attached to dimension 1, and the choice of the next segment candidate to be divided is not difficult to generalise. The easiest generalisation is probably to use separation equations on a one-dimensional multifactorial component. In their principles, the SCC and HMM methods are able to deal with multidimensional variables.

3.2.3. *Extension to a river network*

This question is also related to the need for segmentation for river typology. All the methods can be applied separately on different tributaries of a river network. The point is to retain a reasonable number of reach classes (or to describe them by a reasonable number of states). Only SCC and ergodic HMM methods are able to do this. For the other methods, the classification must be done in the second step. The SCC and ergodic HMM are moreover able to take into account links and nodes.

4. Empirical comparison on real and theoretical cases

4.1. *A real case study*

We suggest exploring here the longitudinal pattern of the active channel width (i.e., combined unvegetated bars and low-flow channel width), which is a key parameter for delineating geomorphic reaches defined by a homogeneous planform and considered a good proxy of ecological assemblages (Frisell et al., 1986; Thorp et al., 2006; Poole, 2010). A braided reach is very different in terms of habitat template from a meandering or a straight reach (Amoros and Petts, 1993; Thorp et al., 2006), and channel width is the primary factor discriminating planform on rivers with active bedload transport and bar development. The active channel width is therefore a good parameter for testing such statistical techniques because its longitudinal pattern can be strongly segmented with homogeneous reaches associated with natural and human controlled discontinuities (e.g., change in sediment regime at

366 confluences, valley morphology, diking, damming, etc.). These spatial struc-
367 tures are usually superimposed on continuums that are also characterised by
368 a general increase in channel width downstream as a result of the discharge
369 increase. The continuum of the Drôme River (SE France), a complex plan-
370 form gravel-bed that is already well known in terms of geomorphology (see
371 Aubry and Piégay, 2001; Alber and Piégay, 2010) was chosen to explore the
372 behaviour of the algorithms. This case is used to run all the methods, but
373 also to help design theoretical templates. First of all, this continuum was
374 disaggregated within elementary 25-m-long spatial units (generally plotted
375 with a 100-m-long step), providing information at a finer scale than the one
376 corresponding to the geomorphic reaches, as explained by the previous au-
377 thors. The data used in this paper are every tenth of these segments, to have
378 reasonable computing time with the slowest methods.

379 4.2. *Testing the methods*

380 Theoretical patterns are useful to exhibit differences between methods
381 and to assess their capacity to deal with various features of spatial stuctures.
382 However, the choice of such patterns is not easy and must take into account
383 the structures encountered in the real world and the underlying models. Pat-
384 terns too close to theoretical models will probably be easily recognised by
385 the corresponding methods and were not representative of real problems. On
386 the other hand, it makes no sense to check a method against a case obviously
387 in contradiction with its assumption. The necessarily intermediate method
388 is an abstraction of real cases, using mainly theoretical patterns with cer-
389 tain testing aims. Lubes-Niel et al. (1998) conducted a comparable study on
390 hydrometeorological data, assessing the power and robustness of statistical
391 tests on data that violated the test assumptions. Our aim differs in that it
392 introduces these patterns instead of alternative statistical assumptions.

393 Fig. 2 provides examples of longitudinal patterns of active channel widths.
394 When applied to the Drôme main stem between km 0 and 75 (nearly 26.5
395 km upstream from the Rhône confluence) for which the mean width is 60.1
396 m (± 52 m) ranging from 5 to 330 m (Fig. 2), different observations can
397 be made: (i) the longitudinal structure is characterised by a rough gradient
398 with the width increasing by 1.07 m/km. This value is a mean calculated
399 from the linear trend linking the width per segment with the longitudinal
400 distance. Nevertheless, this series is also characterised by local peaks such as
401 at km 30 or 54. (ii) Plateaus are also common longitudinal structures (e.g.,
402 homogeneous reaches in terms of mean channel width) separated by stepwise

Fig. 2

shifts or gradients (such as km 7-12, 13-20 or 70-74). However, plateaus are not dominant and can have high inner variability. Transient structures are frequent and succeed one another downstream. We then expect to distinguish segments with a signal characterised by smoothed hills and valleys (understood on the graphs of any variable, not in real geographical space). The focus on km 20-23.5 (Fig. 2B) shows a clear step separating a long narrow reach with an abrupt widening (km 21.4). The focus on km 61-70 shows a local variability where it is difficult to distinguish homogeneous reaches, possibly thresholds at km 63.8 or 65 (Fig. 2C). The different methods were applied to the entire watercourse and plotted separately from km 0 to 75 (Fig. 3) and from km 75 to 101 (Fig.4) with a zoom from km 81 to 87.5 showing the transition areas found by the eHMM method:

Fig. 3,4

- Only one threshold is detected by all the methods distinguishing clear separate reaches in terms of mean width and inner reach variability (A on Fig. 3), F on Fig. 4 missed only by the CE model.
- The number of reaches, at this stage not very closely controlled, varies from 6 (1HMM) to 12 (SCC) and 15 for eHMM, but with repetition in the last case.
- For a moderately large number of states, the eHMM graphs are made easier to read by considering areas with high frequency change as transition areas (Fig. 5).
- Some methods provide a wide range of reach lengths with very short lengths (Pettitt, CE, SCC methods), whereas others provide reaches with more homogeneous lengths (Hubert, eHMM, 1HMM).
- The aggregation patterns of 1HMM and Hubert are very close as are those of the Pettitt and CE methods. The SCC is more specific and also more detailed than the others.
- eHMM provides a good image in the sense that it detected all the thresholds detected by one method or another with fairly homogeneous reaches in terms of length.
- The Hubert test is also fairly efficient, separating the different main structures.

Fig. 5

- 436 • Its simplified version differs only by a minor undetected threshold (G
437 on Fig. 4).
- 438 • The wide reaches corresponding to braided sections are not well de-
439 tected. Peak B (see Fig. 3) is not detected by the Pettitt or the **CE**
440 method, it is fairly narrow for Hubert and **1HMM** compared to **SCC** and
441 **eHMM**. Inversely, peak C is well detected by the Pettitt tests, suggesting
442 a long reach similar to **1HMM**, whereas the **SCC** method does not detect
443 any reach. **CE**, Hubert, and **1HMM** suggest different length.
- 444 • Minor thresholds (D, E, or F) are again variously detected.

445 4.3. Choosing typical theoretical templates

446 This comparison demonstrates the need to better understand the effect
447 of local variability and not only the difference in means, which may also be
448 linked to the resolution of the elementary objects (e.g., the number of indi-
449 viduals in the series), but also the position in the series. In addition, the
450 behaviour of the methods needs to be tested with curvilinear structures to
451 better understand the threshold variability between methods.

452 The methods under study are generally and originally dedicated to identify
453 stepwise shifts. The behaviour of the methods, when reaches have more
454 curvilinear features or transitory reaches are gradual, is less well understood.
455 Consequently, the patterns (Fig. 6 and Table 2) are built with stepwise
456 shifts, but transition segments are introduced, using gradients or pieces of
457 sine functions (on less than a wavelength). As the methods may be sensitive
458 to structures at different scales, the ability to recognise a particular elemen-
459 tary pattern may depend on other nearby patterns. A short step with a
460 gradient in template 1 and with a long step in template 2 is intended to test
461 this hypothesis.

Fig. 6

462 The expected output from the comparisons are:

- 463 • assessment of parameters (thresholds) giving robustness to the detec-
464 tion;
- 465 • control of the number of reaches; and
- 466 • (optionally) detection of reaches with similar properties (here width).

Table 2: comprehensive description of templates (with abscissas of points for resolution 1)

template's number	Description	definition
1	With gradient	Plateaus =400 on intervals (1,21),(87,91),(97,108); =600 on (22,41) ; =0 on (63,86),(92,96); negative slope between 42 and 62
2	Short and long steps	Plateaus =100 on (1,50), (61,70); =200 on (51,60), (71,200) ; =220 on (201,300)
3	Increasing amplitude^b z=1	Plateau after l=250
4 ^a	Symmetry^b z=100 ^c	Plateaus up to l=33 and from l=347

a) For three methods only, see Fig. 13

b) Sine function: $s = 200 + z \sin\left(\frac{l-150}{25}\right) / \sin(4)$

c) An oscillation of 1.5 wavelength between plateaus (not used in this paper) is obtained with $z = 100$, truncated at $l=50$ and $l=250$

4.4. Condition for a meaningful comparison on theoretical cases

Choosing meaningful and fair criteria for comparison is not the least difficulty. If the methods are compared with the criterion used to optimise one and only one of them, there is no uncertainty on the benchmark; but to avoid more subtle bias, comparing methods at similar levels of aggregation is recommended, at least in the first step. The practical application may constrain the size or the number of the segments to find. Generally, each method has a parameter governing this number.

A comprehensive study of the sensitivity of all the methods to their parameters is not required to assess the influence of the parameter governing the number of reaches obtained. The number of reaches happens to be directly the parameter of several methods (CE, Hubert, HMM), and in the case of the HT methods, it is easy to run the method for a level of risk that accepts a large number of reaches and to save and plot the number of reaches as a function of the parameter. The case of the SCC method is different, as plotting the relationship between the number of reaches and the affinity threshold, which is the relevant parameter, requires running the program for many values of the affinity threshold.

Original data have a given resolution (possibly dependent on the objective of

the acquisition), but may be aggregated at a lower resolution and the methods may be sensitive to this resolution. The method may also be sensitive to high frequency variations, which are not within the scope of the delineation. In synthetic data, these variations are simulated by a noise added to the raw templates in Fig. 6. The noise used in the following was drawn from a uniform distribution, which is not the type of distribution assumed in the underlying models (but we are not checking the identification of a model against data simulated with this model). Patterns with and without local variability are presented in Fig. 7 to 12, knowing that the templates without local variability may be too far from real data and from underlying models.

4.5. Comparisons of methods applied on theoretical cases

As a consequence of the pitfalls mentioned in section 4.4, three testing issues are considered: (i) the sensitivity of algorithms to parameters controlling the number of reaches, (ii) the sensitivity to resolution and inner variability, and (iii) the resilience of the methods against the introduction of patterns (such as gradients and hills) not supported by the stochastic models underlying the methods. Note that these three issues may interfere and that the same result may be looked at from different points of view.

4.5.1. Sensitivity to parameters controlling the number of reaches

The study was conducted for the three resolutions (0.5, 1, 2) for the Pettitt method (Fig. 7). The number of reaches is nearly linear with the parameter $\log(\alpha)$ and highly dependent on the resolution, which implies that it is far from its original meaning in the statistical test. The gradient is represented by very unequal steps. The last narrow step is the first one to be missed when the number of reaches decreases. For the SCC method, as the computing time is very long, it was done only for resolution 0.5. Fig. 8 shows a very strong nonlinearity, which means that it is difficult to fit a given number of reaches. Moreover, a number of major steps are missed until a large number of reaches is obtained.

4.5.2. Sensitivity to data resolution and to inner variability

The results are also dependent on noise. Fig. 9 to 11 show the results of six methods out of seven, as the linear 1HMM is presented for the case without noise, on the four templates, and the eHMM for the case with noise, knowing that the identification algorithm of the latter sometimes fails without noise.

Both variants of the Hubert-Kehagias model are represented, which are very similar. The first template is presented in Fig. 9 for resolution 2 and in Fig. 10 for resolution 0.5. As all the methods have problems capturing the pattern with an overly low resolution (length step 2), we studied the other templates only with the highest resolution (length pace 0.5). The second template (Fig. 11) shows that the Pettitt and contrast-enhancing methods do not detect the small last step, while the other methods see it and detect a short reach before the step that was generated by the random process. The results of the third template in Fig. 12 show that noise generally improves the method's performance (except for SCC). The Hubert method, simplified or not, and the HMM and SCC methods without noise yield similar results; while the Pettitt and contrast-enhancing methods tend to concentrate more reaches in areas of greater variation. On the real case, the sequential methods (Pettitt and contrast-enhancing) miss the first peak. The others obtain similar results. As for real cases, for templates with noise and for a large number of states, the eHMM model can yield a very large number of very small reaches with the same mean.

Fig. 10

Fig. 11

Fig. 12

4.5.3. Performance on gradients and curvilinear profiles

The Pettitt and contrast-enhancing models appear to be error-prone in the presence of a gradient (Fig. 10). Contrary to other methods, they split the gradient into very unequal segments, so that it would be impossible to design a post-treatment to identify a gradient. The other methods, though able to 'recognise' the gradient, may be disturbed in another way: the SCC and lHMM models (forced with a small number of states) do not see the narrow step on the right-hand side of the profile. In template 3, though it is difficult to say what should be the best delineation, the results seem better with noise than without, except for the SCC method. In the case without noise, again a separation exists between the Pettitt and contrast-enhancing methods on one hand and the other methods on the other hand, with a longer segment delineated at the top of the hill in the first group.

4.5.4. Treatment of longitudinal repeatability and symmetry

The point of breaking the symmetry in original data is not that important in the real application, as symmetry does not exist in real river networks. Even if the focus is not on the identification of periodic structures, it can be expected that the same pattern should be recognised when repeated along

the river. Fig. 13 shows the results on a symmetrical pattern, which is not developed for all methods. Sequential methods such as HT are unable to provide symmetrical segmentations from symmetrical patterns (Fig. 13-left). Fig. 13 (centre) shows that the nonsequential Hubert method (and SCC, not represented) may also be affected by side effects (the symmetrical sine function is not exactly centred). Fig. 13 (right) shows the CE method, which is the only one to separate the increasing and decreasing parts of a function, which may be valuable for hydraulics issues.

5. Discussion

The interpretation of the comparisons to help select a method is conventionally based on theoretical considerations, empirical results on theoretical or real cases, and computing times. This latest point is not discussed here as we used codes under different systems and written in different languages. The theoretical question is the nature of the underlying model: continuous or discontinuous, periodic or aperiodic, univariate or multivariate.

At the hydrographic network scale, scientific debate continues about the existence and type of discontinuities and homogeneous reaches. Some authors consider that discontinuities are arbitrary, the river course being mainly characterised by a transitory form. This is notably the case between channel patterns, given that the river often passes progressively from a truly braided pattern to a truly meandering one with transitory hybrid patterns between the two. This is the essence of the so-called geomorphic continuum. Other authors considered that discrete structures segment the continuum and considered this continuum a set of longitudinal homogeneous segments/reaches with distinct properties. In this debate, the hydrographic networks, or at least long segments of several tens of kilometers are recognised as complex features characterised by gradual changes downstream or distinct homogeneous reaches depending on the observation scale as well as the indicators selected. Amongst the different geomorphic variables, the average channel slope is most often a continuous variable, whereas the average channel width is more frequently characterised by abrupt discontinuities.

Whether we need an exclusive separation of reaches or accept transition areas will influence the choice of the method. The tests done here confirm that the longitudinal patterns are complex, combining plateaus, gradual transitions, clearer steps, local peaks, and period structures of different amplitudes and frequencies. It is therefore difficult to be confident with a single segmenta-

tion method and comparisons between them are useful to distinguish robust discontinuities and others that are less significant.

Four key comments emerge from this comparison: (i) Only part of the meaningful geomorphic pattern is seen if we consider only one variable. We must consider this type of approach as a first step in the geomorphic characterisation, and this variable must be selected carefully because its segmentation will have consequences on the calculation of the other variables. We consider the active channel or the floodplain widths as good preliminary geomorphic variables for establishing a first clustering because they support major planimetric discontinuities and are then fairly integrative whereas the slope may show for example more gradual evolution longitudinally. (ii) The longitudinal structures are dynamic in time and are adjusted at a different time scale, but it is difficult to infer these dynamics from a snapshot of longitudinal structures. Multitemporal series of a single variable should also be consistent to distinguish permanent structures from transitory ones in time. (iii) We still know little about scaling, how the different structures are nested within each other. Following Frissel et al. (1986), the conceptual framework is clarified, but it is not validated by data. It is still unclear whether the scale-dependent structures are nested or partly independent so that chaotic organisation may prevail over nested organisation. (iv) The signal results from different drivers so that its sequencing based on a single statistical procedure (threshold, periodicity, or gradient detection) is a significant simplification; but we first need to better understand the scale organisation to reconsider which statistical tools could be appropriate, whether or not they are combined.

The identification of periodic structures is hindered by the multiplicity of spatial signatures (monotone, periodic, chaotic, variously stationary, etc. of geomorphic variables, the scalar dependence of fluvial forms and their spatial variations, and the unclear consequences of measurement errors in data.

Some periodic structures exist within some of the reaches because of hydraulic processes structuring channel forms, notably along sections characterised by sequences of pools and riffles (Montgomery and Buffington, 1997), which may provide inner disrupting structures complexifying the detections. Several statistical tools, such as spectral analysis or auto-correlation, usually used to describe temporal organisation, have already been applied to characterise longitudinal structures along river continuum, notably to highlight alternating hydraulic features. The Fourier transform has been used to show the longitudinal organisation of the water velocity framework (Hardisty, 1993) and the channel width and slope (Nakamura and Swanson, 1993). Spa-

631 tial auto-correlation functions, Geary's c and Moran's I mainly, more rarely
 632 non-ergodic correlation and covariance, have been applied to illustrate the
 633 spatial regularity of hydraulic structures or fluvial forms downstream (Aubry
 634 and Piégay, 2001). Madej (1999) calculated the Moran's I to characterise
 635 the longitudinal regularity of pool-riffle sequences along a long profile and
 636 the autocorrelation lag as a scalar index (frequency of changes in geomor-
 637 phic features). The autocorrelation functions were also used to evaluate the
 638 periodicity of hydraulic parameters (grain and form roughness), the index be-
 639 ing introduced in hydraulic formulae to predict mean flow velocity (Clifford
 640 et al., 1992). The longitudinal structure has also been studied in terms of the
 641 probability of the occurrence of geomorphic features (pool, cascades, rapids,
 642 riffles, etc.) using the Markov chain (Grant et al., 1990). The aim of period-
 643 icity detection, different from ours explained in the introduction, is then to
 644 identify the frequency of a given facies sequence (the pool-riffle sequence for
 645 example) using a transitional probability matrix where each cell corresponds
 646 to the probability that a facies can follow another one downstream. The size
 647 effect has also been considered in such studies, based notably on the fractal
 648 analysis at a hydrographic network scale (Gao and Xia, 1996).
 649 Periodic structures were not considered the subject of this study but only as
 650 disturbances likely to be encountered when focusing on segment/reach scale
 651 for which discrete structures with fairly clear boundaries and nonperiodic
 652 structure seems to be easily detected. Consequently, we discarded the meth-
 653 ods dedicated to recognising periodic structures because we assume they were
 654 prevailing at a local scale but are not encountered at the scale of the river
 655 reaches. Nevertheless, this comparison of algorithms showed that sinusoidal
 656 structures are frequent, sometimes periodic, and that establishing clear dif-
 657 ferences in scale levels is difficult.
 658 Beyond the undeniable result that different methods yield different results,
 659 the comparison on theoretical templates cannot settle the scientific debate
 660 but can contribute by bringing out the biases stemming from the methods.
 661 No method is absolutely superior to all the others. However, the methods
 662 that are run sequentially (the partition at order $n + 1$ takes all points of the
 663 partition at order n), the Pettitt and contrast-enhancing methods, which are
 664 consequently faster, have some propension to determine segments that are
 665 too unequal in length. This suggests a flaw in the choice of the next reach to
 666 divide rather than on the detection of heterogeneity. The Hubert method,
 667 its simplified variant, and the HMM methods produce — with adequate pa-
 668 rameterisation and a reasonable number of reaches — very few failures in

669 detecting subpatterns introduced in the templates.
670 The interpretation problems with the interference of parameterisation is not
671 a methodological issue limited to a benchmark. In real application to large
672 data sets, it is unlikely that a method might be optimal at any scale and
673 on the whole network. So the nature of solutions found with nonoptimal
674 parameterisation is part of the problem. In a large network, we should also
675 have to take into account the upstream-downstream trends that appear in
676 the observed data.
677 Algorithms are moderately sensitive to noise. We did not multiply the num-
678 ber of trials by tuning the amplitude of noise, but only studied a few cases
679 with and without noise. The latest case is an extreme and unrealistic simpli-
680 fication, in contradiction with the assumptions underlying models. However,
681 it shows that the methods generally resist this simplification with the adapted
682 parameters and changes in patterns found. In particular, undisturbed seg-
683 ments with constant gradients are easily recognised as a sequence of equal
684 subsegments, allowing post-processing; but this procontrainperty is lost when
685 there is noise.
686 Let us finally come back to the ‘other features’ of section 3.2, parameteri-
687 sation, multidimensional, and river network extension. The benchmark was
688 done on univariate series and highlighted only the parameterisation issue.
689 However, as stated above, delineation is often the means for drawing up a
690 typology that can be used as a tool for sustainable river management or for
691 further scientific investigation. In this context, the main aim is to select
692 the appropriate variable, the one that is sufficiently integrative to provide a
693 preliminary segmentation and to choose the appropriate algorithm to iden-
694 tify the proper boundaries. Transient gradients and merging of neighbouring
695 segments can be performed at a later stage, for example, by linear correla-
696 tion and clustering. As for the last one, it is also better from a geomorphic
697 point of view because it is based on a wider set of variables. The delineation
698 methodology must be adapted to the ultimate aim.

699 6. Conclusion

700 Four templates were designed as a trade-off between realism, simplifica-
701 tion, and low satisfaction of the assumptions underlying the methods under
702 study. On these templates and on real data, seven methods belonging to four
703 families were run.
704 Thresholds of statistical tests and other parameters control the number of

705 reaches obtained. Constraining the number of reaches, whether or not it is
706 directly a parameter of the method, is useful to obtain comparable results
707 for different methods. However, this number may be difficult to control in
708 the SCC method because of the possibility of a critical value of the affinity
709 threshold parameter.

710 Benchmarking should be done first, allowing ‘optimal’ parameterisation of
711 each individual method; secondly looking at downgraded application con-
712 ditions as it is unlikely that optimisation can be done simultaneously on
713 different parts of a hydrographic network. These downgraded parameterisa-
714 tions result in omitting certain patterns that are obvious from a naive point
715 of view. This behaviour may depend on the location of the pattern in the
716 system.

717 In particular, the thresholds and parameters ensuring a given number of
718 groups depend on the resolution of the data; but even if the number of
719 groups is forced to equal values, the partition will not be the same at differ-
720 ent resolutions. As the meaning of statistical tests — their interpretation
721 as the probability of exceeding a threshold — is somewhat dubious when
722 they are applied in a context different from their fundamental hypothesis;
723 the thresholds become mere parameters, possibly used outside their nominal
724 values, tuned to satisfy other criteria.

725 It should be noted that broader assumptions are allowed by the ergodic HMM
726 method. If delineation of homogeneous and exclusive segments is not a com-
727 pulsory objective, it may be interesting to analyse the watercourse with this
728 method. As it is able to point out patterns other than steps, such as repetition
729 of patterns, transition areas or high frequency alternance of substructures,
730 without increasing the degree of freedom, it allows to revisit the objectives of
731 delineating homogeneous segments and at least to highlight its arbitrariness.
In other words, the method reveals continuum and discontinuum.

732

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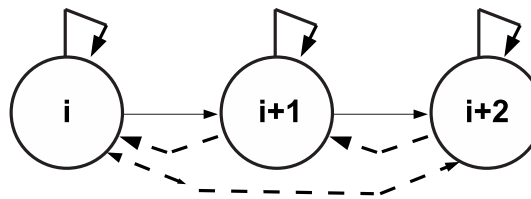


Figure 1: Topology of an ergodic HMM: the dashed lines correspond to the authorised transitions in the ergodic model vs. the linear model

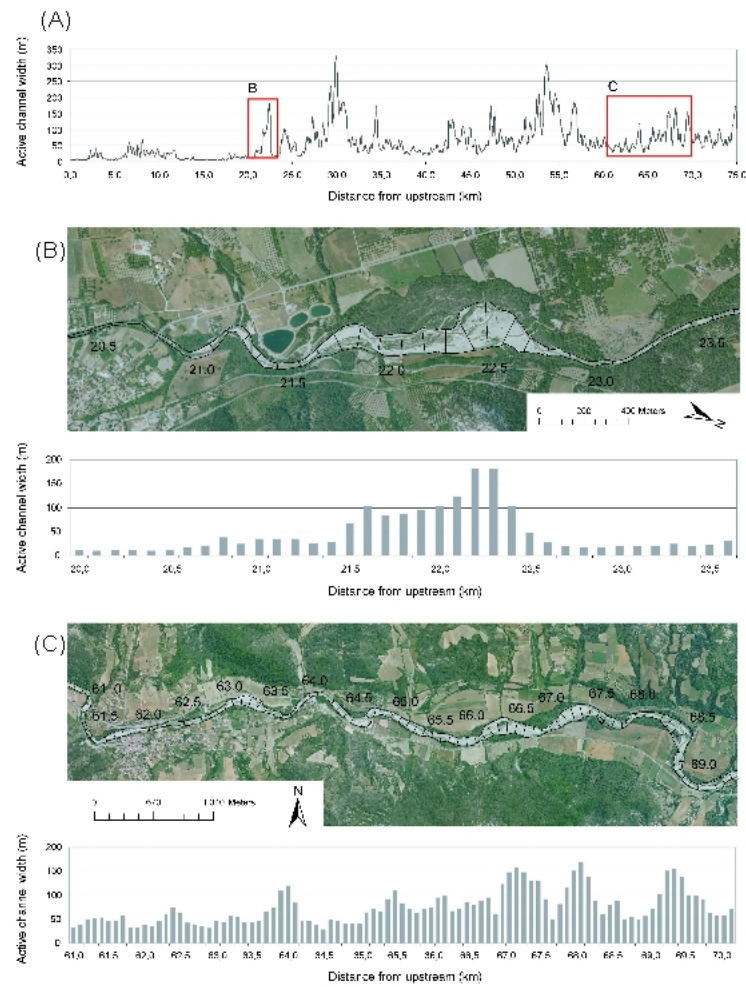


Figure 2: The Drôme River showing (A) longitudinal evolution of the active channel width showing a complex pattern with plateaus as well as hills, valleys, and gradients. Evident stepwise shifts are observed (B) as well as reaches with a high local variability and less evident shifts (C). Length of segments is 100 m

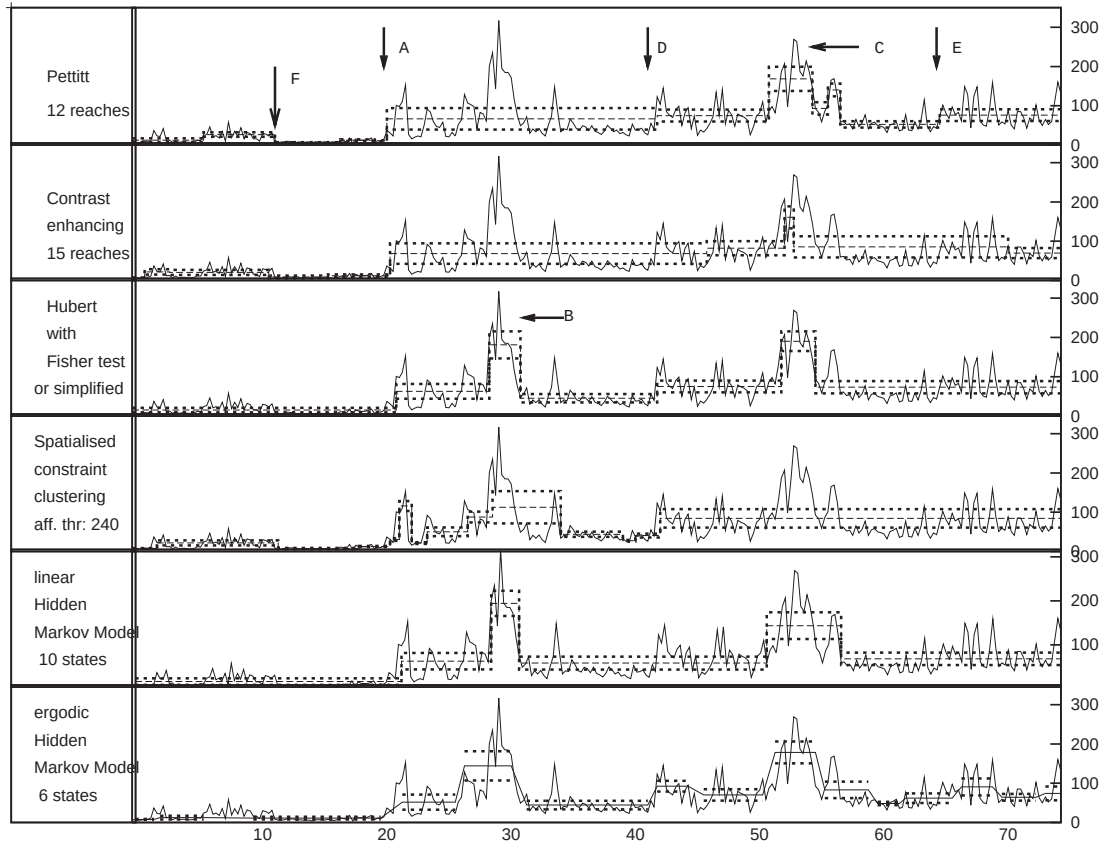


Figure 3: Drôme River, active channel width, mean, and half standard error for reaches found by all methods fitted on the whole river but represented on the upstream part corresponding to Fig. 2. For ergodic HMM, homogeneous sectors for no less than six points. For SCC, aff. thr. is the affinity threshold, which has the dimension of the variable. Note that the Pettitt, CE and SCC methods are parameterised with more reaches than the Hubert and HMM methods

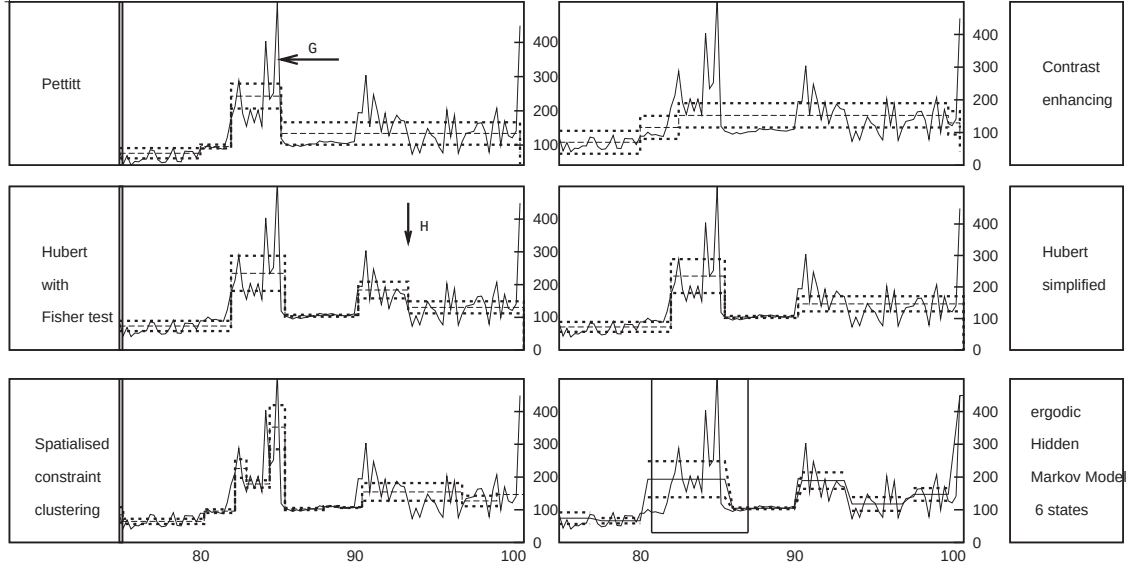


Figure 4: Part of Drôme River downstream reaches on Fig. 3. All methods with the same optimisation as on Fig. 3. See zoom of the rectangle on the eHMM subfigure in Fig. 5.

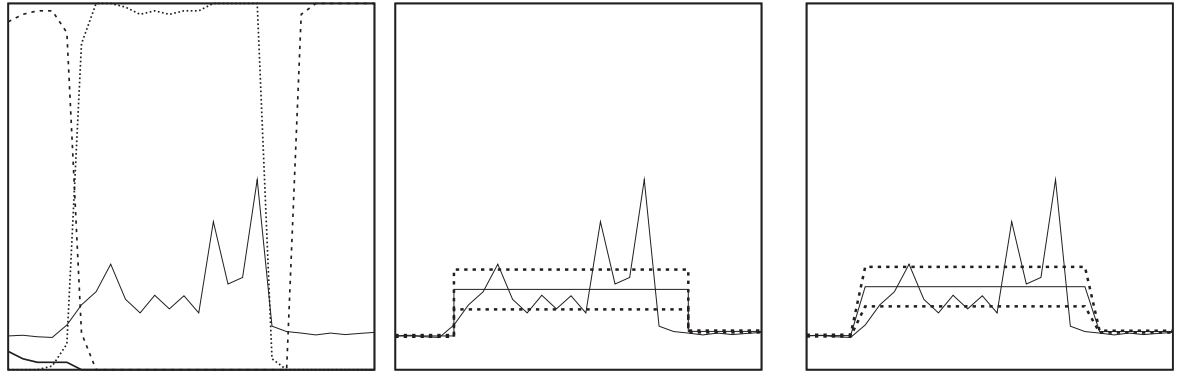


Figure 5: Zoom (km 81 to 87.5) on the Drôme River, active channel width, ergodic HMM, probabilities of six states. Left: probabilities of different states; centre: reaches separated on most probable state; right: transition areas for less than six adjacent points having the same most probable state.

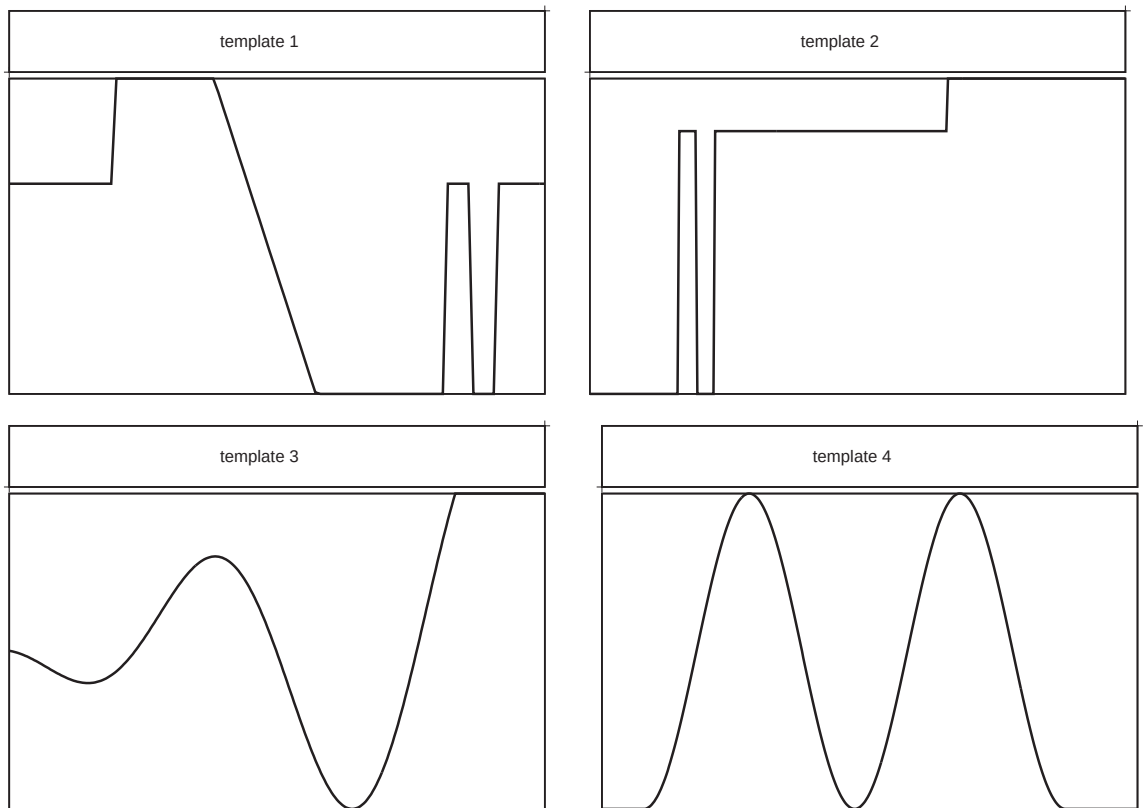


Figure 6: The four templates (without noise).

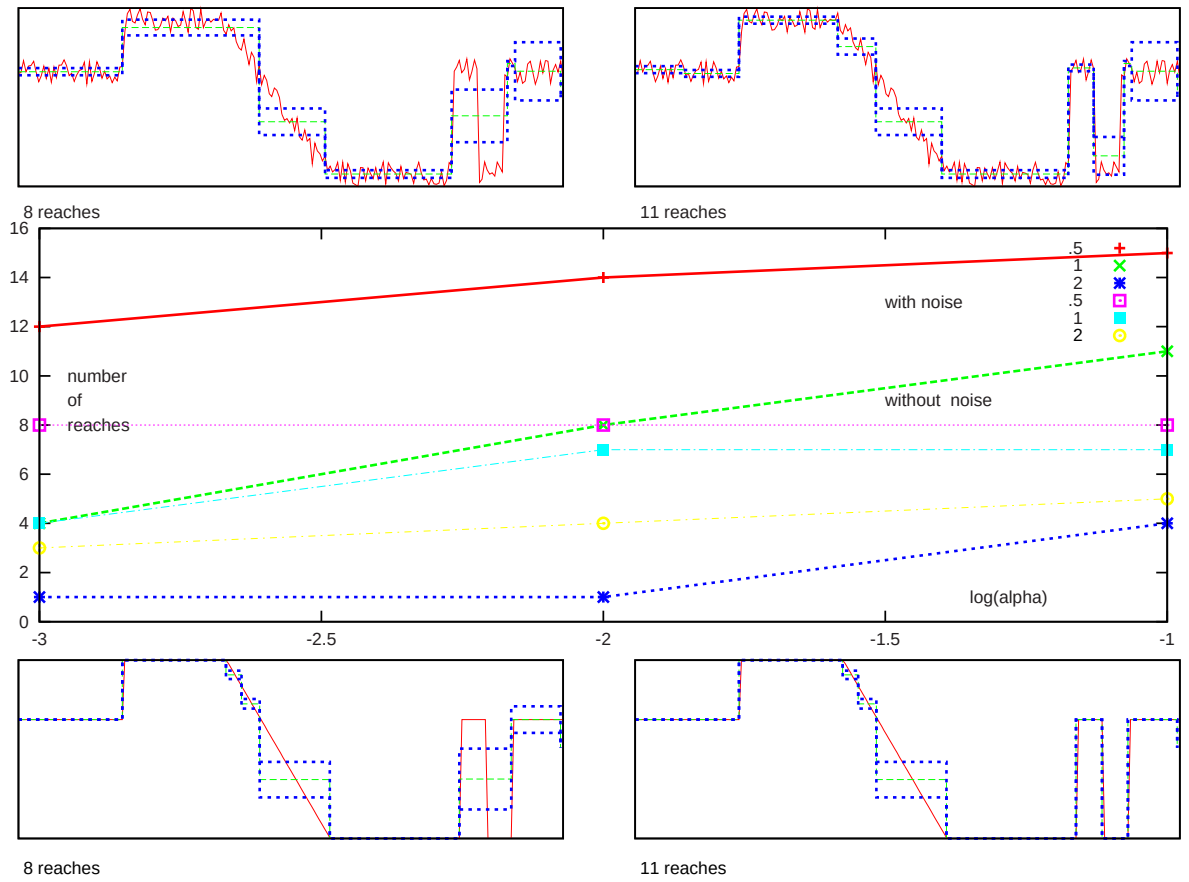


Figure 7: Sensitivity to α (probability of 2nd type risk) and resolution in the the Pettitt method, top: with noise; bottom: without noise; left: low probability of wrong acceptance of homogeneity; right: high probability. Top and bottom graphs are all for resolution 0.5.

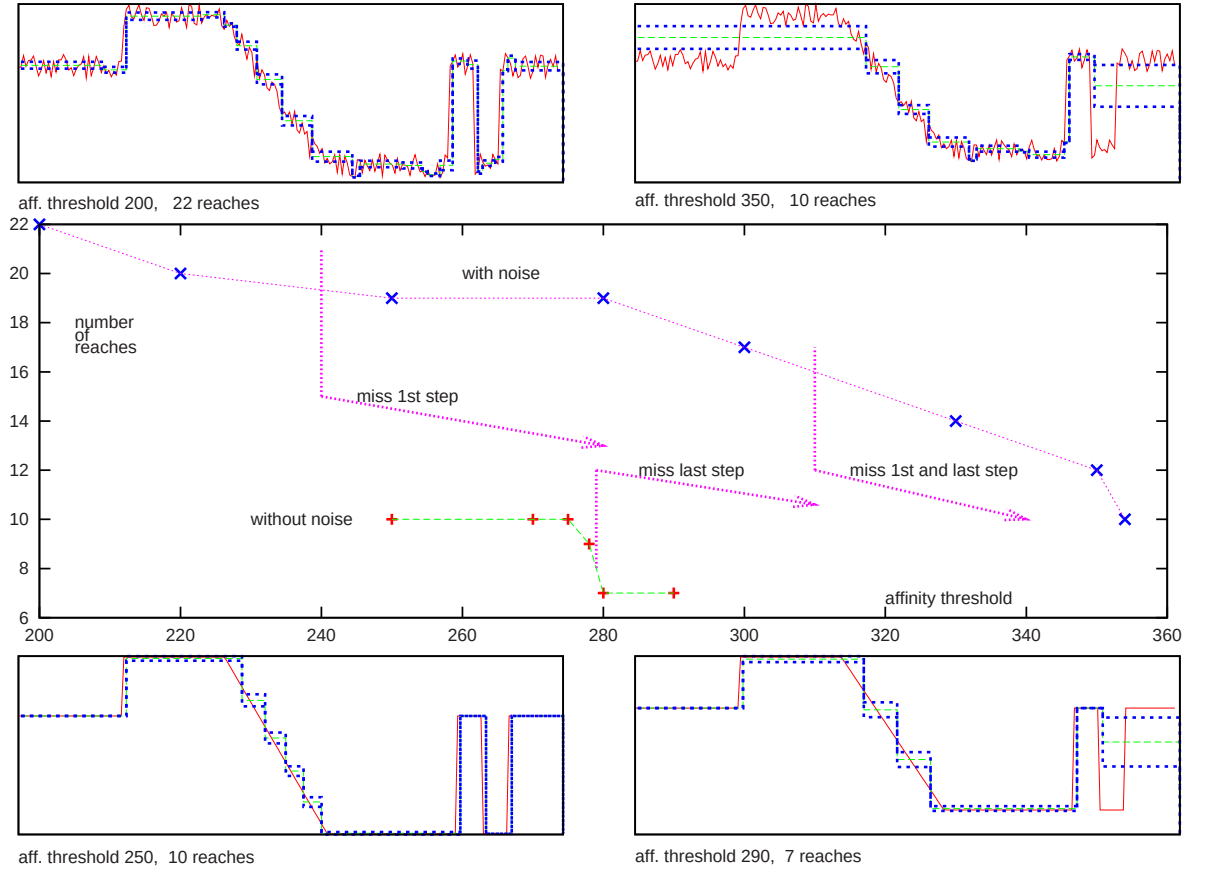


Figure 8: Sensitivity to affinity threshold in the SCC method. Top: with noise; bottom: without noise; left: low affinity threshold; right: high affinity threshold.

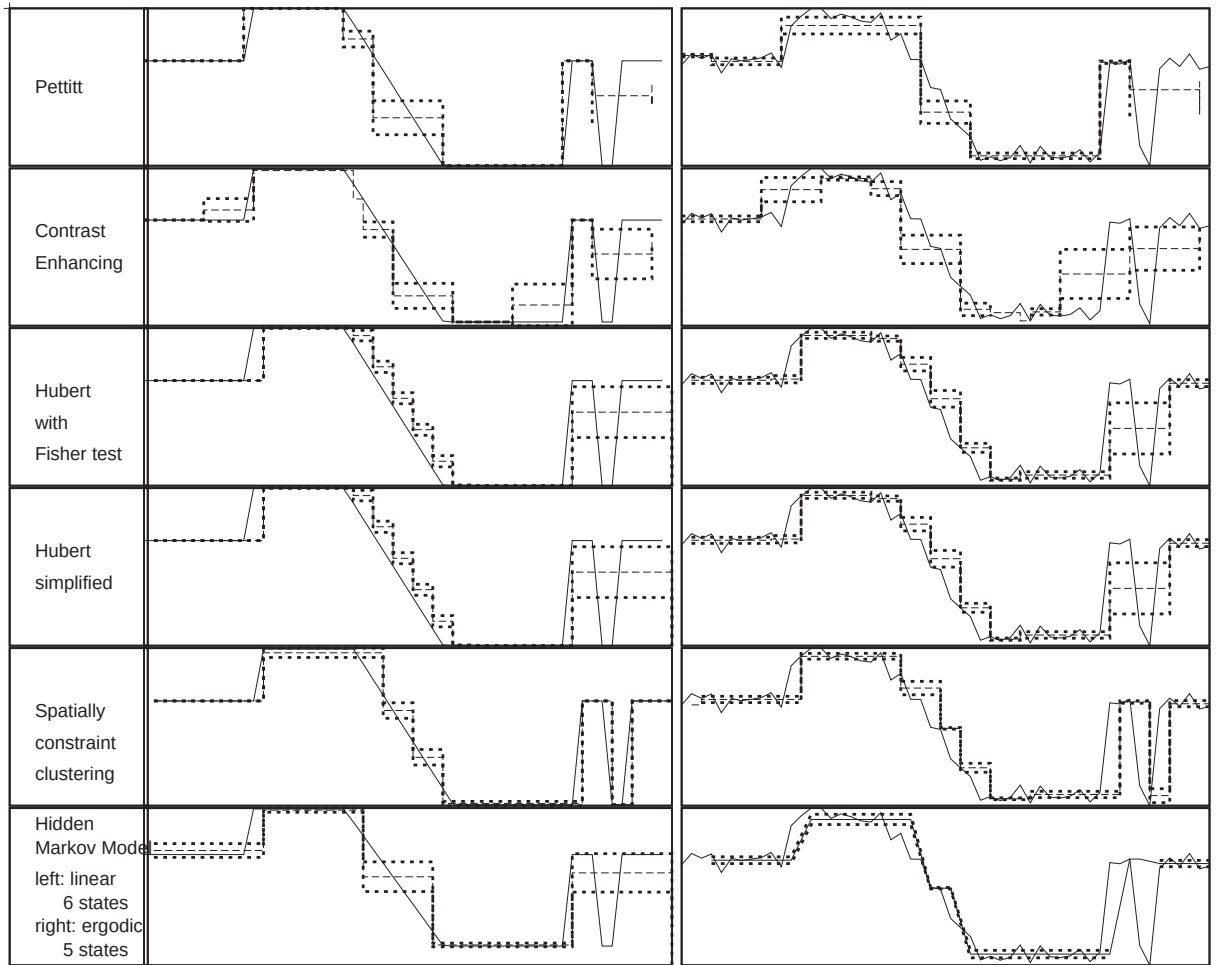


Figure 9: 1st template, resolution 2. Left: without noise; right: with noise.

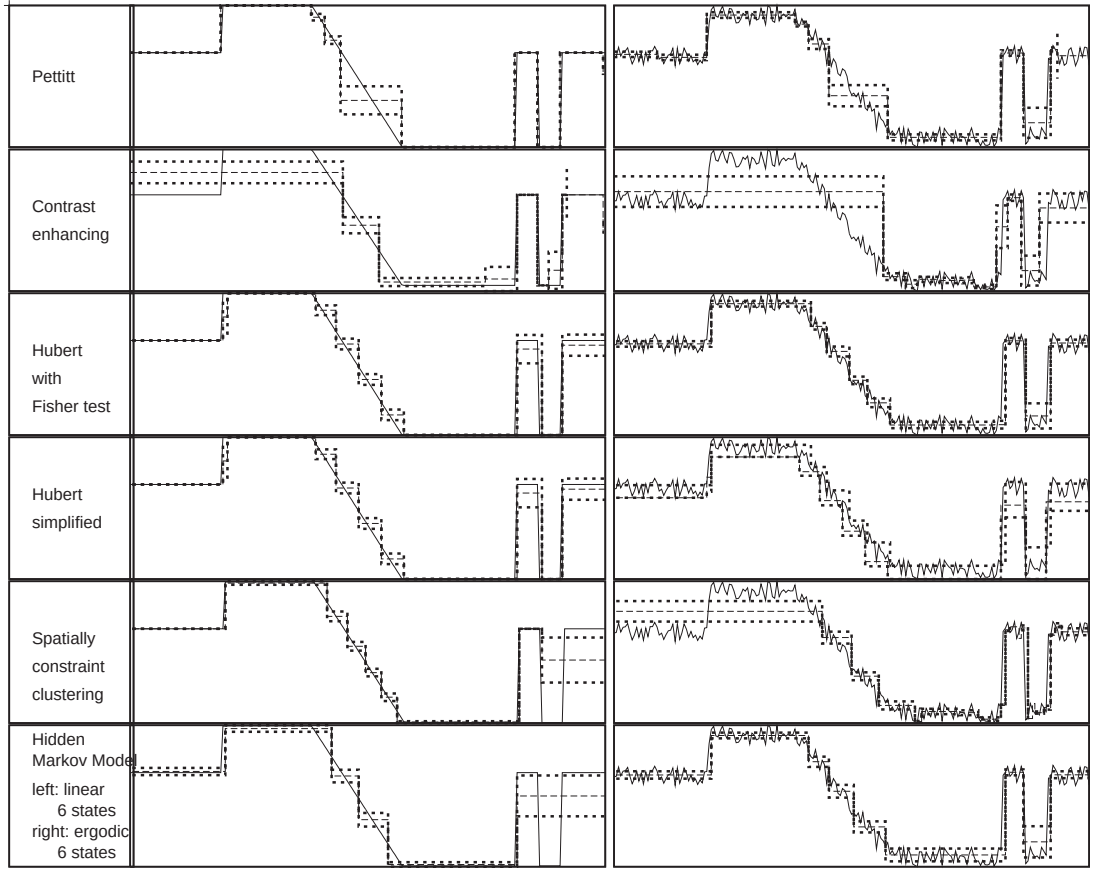


Figure 10: 1st template, resolution 0.5. Left without noise; right: with noise. The linear HMM is not optimal but presented to show the same number of states as the ergodic HMM.

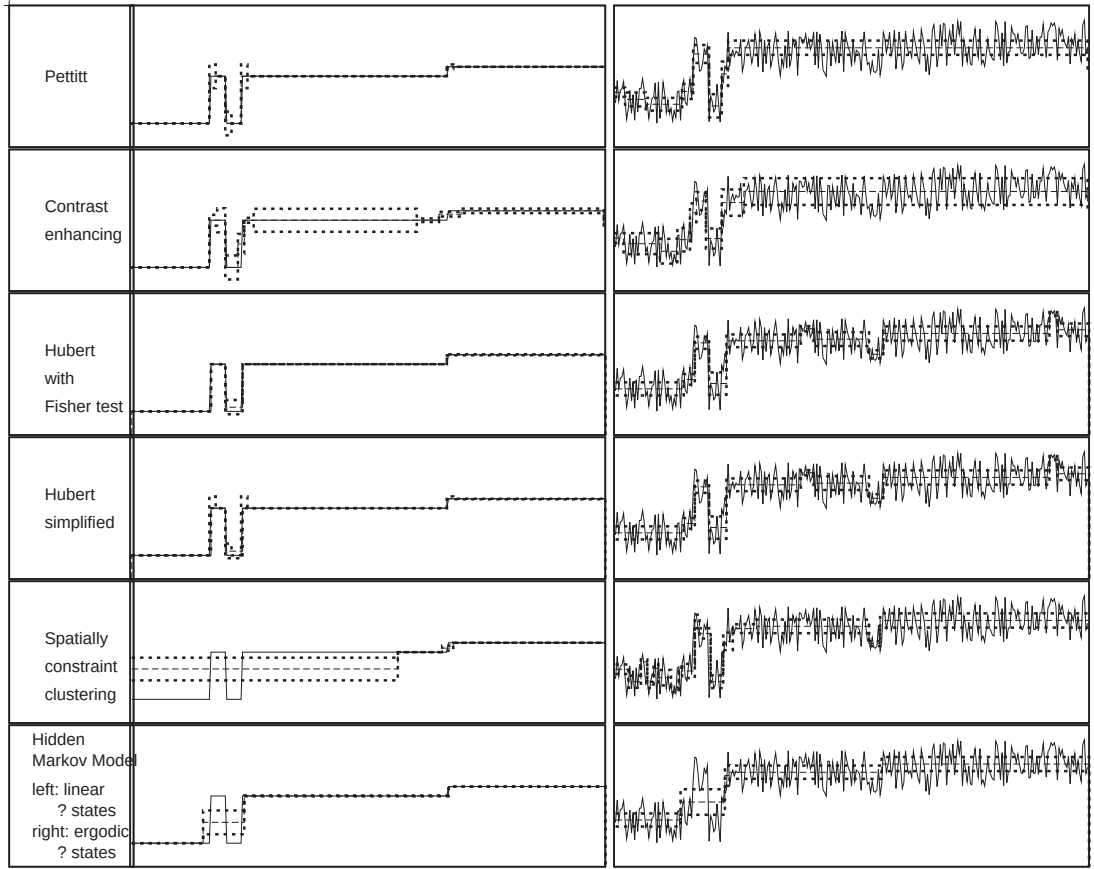


Figure 11: 2nd template, with noise, all methods.

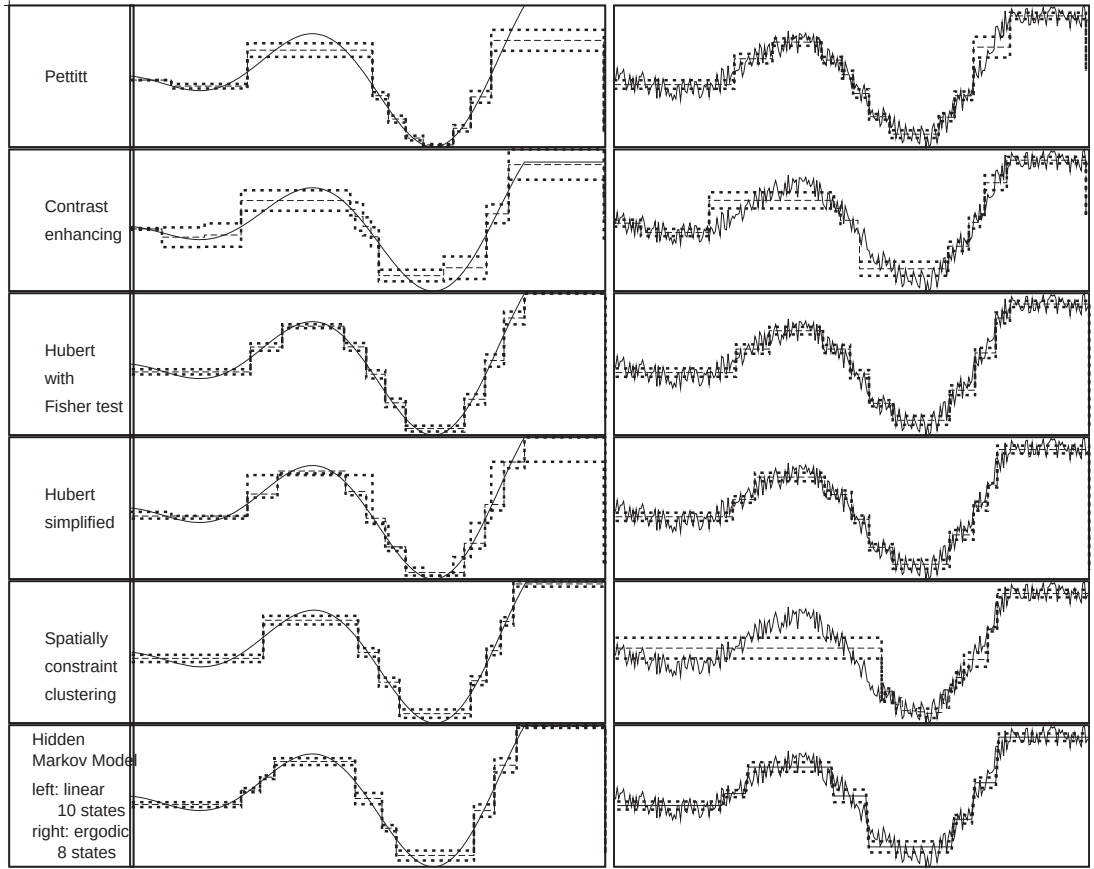


Figure 12: 3^{rd} template. Left without noise; right: with noise.

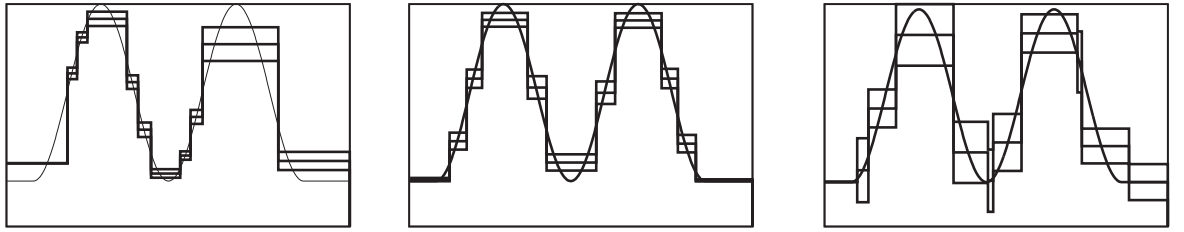


Figure 13: 4th template, treatment of symmetry in different methods. Left: Pettitt; centre: Hubert(simplified); right: contrast-enhancing.