

Tools for assessing European streams with macroinvertebrates: major results and conclusions from the STAR project

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Abstract

This short paper summarises the information developed in the EU funded research project STAR on autecology databases, metrics, multimetrics and community approaches. For Europe the WFD implementation gave an important stimulus for the development of ecology based assessment techniques. Along with the development of metrics and multimetrics indices taxalists and autecological information were strongly improved. Recommendations are given to further develop ecological assessment in European streams and rivers.

Introduction

The systematic use of biological responses to evaluate changes in the environment with the intent to use this information in a water quality control program is defined biological assessment (Matthews et al., 1982). The biological response is measured by using biological indicators. In the first decades of the 20th century biological assessment mostly used simple straightforward techniques (Hynes, 1960; Hellawell, 1978) related to organic waste pollution. Within these methodologies the saprobic approaches and indices (as described by e.g., Kolkwitz & Marsson, 1902, 1908, 1909; Forbes & Richardson, 1913; Ellis, 1937; Liebmann, 1962; Sládeček, 1973) have been widely used in many central and eastern European countries. During the last decades of the 20th century these biological assessments more and more appeared to be low sensitive, superficial, robust to natural variation, and unpredictable as the impacts of organic pollution decrease due to enhanced wastewater treatment techniques and

facilities. The traditional quality assessment approaches failed after the impairment of rivers got mixed with other environmental disturbances. Furthermore, using biotic indices (e.g., Chandler, 1970; Woodiwiss, 1980; Armitage et al., 1983) the condition of sites near the ends of the measuring scale were easy to judge but the middle part of the scale, thus the moderately degraded sites appeared not (Tolkamp, 1985). Traditional biological assessment methods no longer provided a sufficient tool for integrated water management due to their restricted approach to one or a few aspects of the aquatic ecosystem.

In ecological assessment the corresponding environment is added to the biological one (Odum, 1971) to reflect together the ecosystem as a whole. To assess a running water system one should use a high variety of parameters reflecting the structure and functioning of the ecosystem (Cairns, 1975; Frey, 1975; Karr et al., 1986) and also reflecting different types of disturbance (e.g., Nelson, 1990; Richter et al., 1996; Roth et al., 1996). On the other hand Fore et al. (1996) stated

that it would be wrong to think the more parameters added, the higher probability of an accurate diagnoses.

Still, the presence, numbers, and condition of specific species of aquatic macroinvertebrates, fish, algae and macrophytes can provide accurate information about the quality of a specific stream or river. Ecologists try to understand this information and use it to support management. This summary shows in short the development of community approaches and multimetric indices, as both of these tools ecologists use to reach their objectives.

Single metrics and indices

The more conventional approach in using individual species composition and/or abundances related measures was to select a biological parameter that referred to a one factor range of change in environmental conditions, mostly related to a very strong and obvious stressor, and to evaluate that parameter (e.g., species distributions, abundance trends), such as the saprobic indices mentioned in the introduction. Such single biological parameter was interpreted with a summary statement about the water quality, by using an index or metric score. This approach is limited in that the key parameter emphasised may not reflect the overall ecological status.

Nevertheless the recent bio-monitoring is still based on biological indicators. A biological indicator reflects the biological response to chemical, physical or biological properties of a water body or to the overall ecological condition (Karr & Dudley, 1981; Rosenberg & Resh, 1993; Simon & Davies, 1995; Verdonschot, 2000). A biological indicator can be used to characterise the current status, can identify major ecosystem stress and can track or predict significant change of the status of a water body. In general, an indicator has a diagnostic feature. Indices or metrics make use of indicators and combine them into a numerical value or score.

Following Karr & Chu (1999) metrics are defined as “measurable parts or processes of a biological system empirically shown to change in value along a gradient of human influence”. An index or metric is useful when it is:

- (1) relevant to the ecosystem under study and to the specified objectives;
- (2) sensitive to stressors;
- (3) able to provide a response that can be discriminated from natural variation;
- (4) environmentally benign to measure in the aquatic environment;
- (5) cost-effective to sample.

A number of indices or metrics have been developed and subsequently tested in field surveys of different aquatic organism groups; from the early saprobic systems (e.g., Kolkwitz & Marsson, 1902, 1908, 1909; Pantle & Buck, 1955; Zelinka & Marvan, 1961; Liebmann, 1962; Sládeček, 1973), diversity indices (e.g., Shannon & Weaver, 1949; Washington, 1984; Boyle et al., 1990) to biotic indices (Woodiwiss, 1964; Tuffery & Verneaux, 1968; BMWP, 1979; De Pauw & Vanhoren, 1983; Andersen et al., 1994 and others). Biotic indices and biotic scores use both a saprobic rank and a diversity measure and thus combine a richness measure and a (mostly organic) pollution tolerance measure (Metcalf, 1989; De Pauw et al., 1992). The biotic index therefore could be classified as a bimetric.

Multimetric indices

The next logical step in metric development was to combine a number of different metrics, each of which provides information on an ecosystem feature and when integrated, performs as an overall indicator of ecological conditions of a water body. The value of a multimetric index is that such an approach integrates information from different ecosystem components and evaluates, with reference to biogeography, a number of single ecologically based indices (Karr et al., 1986; Plafkin et al., 1989; Barbour et al., 1995). Such multimetric assessments provide detection capability over a broader range and nature of stressors and give a more complete picture of ecological conditions than single bio- or ecological indicators.

The US EPA defined a multimetric index as an index that combines indicators, or metrics, into a single index value. Each metric is tested and calibrated to a scale and transformed into a unitless score prior to being aggregated into a multimetric

index. Both the index and the metrics are useful in assessing and diagnosing ecological condition.

A large number of metrics has been developed (e.g., Fausch et al., 1990; Karr, 1991; Karr & Kerans, 1992). The Index of Biotic Integrity (IBI) was probably the first and most original multimetric index (Karr, 1981), and was based on fish. It originally included 12 metrics that reflected fish species richness and composition, number and abundance of indicator species, trophic organisation and function, reproductive behaviour, fish abundance, and condition of individual fish. These metrics reflect the ecosystem characteristics of food source, water quality, habitat structure, flow regime and biotic interactions. Later on, other multimetrics were developed that included the benthic macroinvertebrate assemblage (e.g., Invertebrate Community Index (ICI); Ohio EPA, 1987; Plafkin et al., 1989; Kerans & Karr, 1994), or the macrophytes (Nelson, 1990). Barbour et al. (1992) presented the conceptual base for the multimetrics approach in which the benthic community health is composed of community structure, community balance and functional feeding groups, and in combination with habitat quality, an integrated assessment is obtained (Verdonschot, 2000).

Consequently, all multimetrics were and are based on ecological attributes of biological communities. Eight major groups of metrics can be distinguished (adapted after Resh & Jackson, 1993; Thorne & Williams, 1997):

- richness measures (e.g., number of taxa, number of EPT taxa, number of Chironomidae taxa); often these metrics are considered to be sensitive to organic pollution;
- enumerations or composition measures (e.g., number of individuals, % of the total EPT taxa (sensitive) and chironomids (tolerant), % dominant taxon, number of intolerant taxa, % Oligochaeta, sediment tolerant taxa); often these metrics are considered to increase in dominance of one or more taxa due to pollution or disturbance;
- diversity measures (e.g., Shannon–Wiener Index, sequential comparison index); often these metrics are considered to decrease with increasing disturbance;
- similarity/loss measures (e.g., number of taxa in common, community loss index, Bray–Curtis

index); these metrics use comparisons between sites (reference vs. disturbed sites);

- tolerance/intolerance measures or biotic indices (e.g., saprobic index and Hilsenhoff's family biotic index, BMWP score, ASPT score); the last two metrics rely on the assignment of (in-) tolerance values to taxa and include richness;
- functional and trophic measures (e.g., % of functional feeding groups, % habitat or current preferences, % locomotion types, longitudinal zonation index); these metrics use the alteration in food types, habitats and environmental conditions under different types of disturbance;
- (life) strategy metrics; the metrics use the biological life strategy features like, length of the lifecycle, number of eggs or diapause;
- condition metrics; these metrics use features of the condition or health of a specimen (e.g., percent of individuals that are diseased, deformed, or fish that have eroded fins, lesions, or tumours).

The common approach is to define a number of metrics that individually provide information on each ecosystem characteristic and when integrated, function as an overall indicator of biological condition.

The scores of the individual metrics are aggregated to calculate the multimetric index (e.g., Karr, 1981; Barbour et al., 1996). The multimetrics establish relative values for each single metric based on comparison of values for the best available habitat (with minimal human disturbance) to those areas which are strongly disturbed (see Verdonschot, 2000).

Autecology databases

The important base for many metrics or indices is the taxonomical status of each collected organism. The AQEM/STAR macroinvertebrate taxalist includes the updated taxonomical information of aquatic orders, families and species, as well as the species occurrences in 14 European countries (Schmidt-Kloiber et al., 2006).

Autecology databases for aquatic species cover ecological attributes of various ecological preferences (such as tolerances and preferences for current, acidity, organic load, substrate, trophic

state and toxic substances) and of strategy or trait features like length of lifecycle, number of eggs, short-winged. These databases are crucial to support the use of metrics. Such lists were compiled already when the first saprobic indices were drafted (e.g., Kolkwitz & Marsson, 1908, 1909; Sládeček, 1973). In the last decade several databases were published, such as Verdonschot (1990), van der Hoek & Verdonschot (1994), Moog (1995), Schmedtje & Colling (1996), Šporka (2003). These list became more operational by including them in software packages, like ECOPROF (Moog et al., 2001) and the AQEM assessment program (AQEM consortium, 2002). Schmidt-Kloiber et al. (2006) list the available autecological information in the AQEM/STAR database. Most common in this database are the ecological attributes of oxygen demand (saprobic indices), stream zonation, current and substrate preferences, feeding and locomotion types. During the EU funded project, Euro-limpacs (www.eurolimpacs.ucl.ac.uk, Contract No: GOCE-CT-2003-505540) this database serves as a basic data source and will be extended to include ecological parameters, which are assumed to be sensitive to direct or indirect impacts of climate change. As a final outcome of this project all autecological parameters will be made available to the scientific public via a website for manifold multiple uses, e.g., the development of future assessment systems.

Community assessment

With the upcoming use of multivariate analysis techniques in ecology, aquatic ecologists started to explore relationships between whole taxa lists and accompanying environmental parameters (Verdonschot, 2000). Wright et al. (1984) used multivariate analysis techniques to classify unpolluted running water sites and to predict community types from environmental data (the River Invertebrate Prediction and Classification System (RIVPACS)). RIVPACS offered a prediction of the macroinvertebrate composition to be expected at a given site from a small number of environmental parameters recorded. By comparing the fauna observed (at species or at family level) with the expected or "target" fauna predicted, a measure of site quality was obtained (Wright et al., 1989, 2000).

The Australian River Assessment Scheme (AUSRIVAS) is based on the RIVPACS model. The differences are that the major habitats are sampled and modelled separately and that different models are used for different bioregions over Australia (Simpson & Norris, 2000).

Verdonschot (1990) conducted a large extensive data collection and multivariate analysis of macroinvertebrates in surface waters in the Netherlands. Verdonschot described macrofaunal site groups (cenotypes), which are recognised on the basis of environmental variables and the abundance of taxa. His cenotypes were described as overlapping entities with limited internal variation, no clear boundaries were provided only a recognisable centroid. The cenotypes are mutually related in terms of key factors, which represent major ecological processes. The cenotypes and their mutual relationships form a web that offers an ecological basis for the daily practice of water and nature management (Verdonschot, 1991). The web allows the development of water quality objectives, provides a tool to monitor and assess, indicates targets and guides the management and restoration of water bodies (Verdonschot & Nijboer, 2000).

Other multivariate approaches using different techniques are described by amongst others Johnson, 1998; Hawkins et al., 2000; Reynoldson et al., 2000. The PERLA system (Kokeš et al., 2006) involves a network of reference sites, a database of reference sites involving both respective biotic and abiotic data, and a prediction model. It is an expansion of the RIVPACS model. As most multivariate based approaches it assesses the overall condition of the ecosystem and as such is not stressor specific.

AQEM

The AQEM project (The Development and Testing of an Integrated Assessment System for the Ecological Quality of Streams and Rivers throughout Europe using Benthic Macroinvertebrates. Contract no.: EVK1-CT-1999-00027; www.aqem.de) was carried out between 2000 and 2002. The development of the AQEM ecological quality assessment system was based on newly collected data that covered both the benthic

macroinvertebrate fauna and general stream characteristics. The data were collected by 8 countries (Austria, Czech Republic, Germany, Greece, Italy, The Netherlands, Portugal and Sweden). Generally, to develop the assessment system the following steps were taken (Hering et al., 2004):

- deriving a stream-type specific classification, which reflects the degradation of a site, based either on abiotic data recorded in a harmonised “site protocol” or on the biotic composition;
- testing of various attributes of the assemblage (i.e., metrics) with the goal to identify those most effective in measuring the degradation of the stream;
 - the starting point is the taxa list obtained from the sampling site, which is to be assessed;
 - based on this taxa list a number of metrics is calculated;
 - generally, the metric’s results are individually converted into scores by comparing their values with the values of the same metrics in stream-type specific reference conditions;
- selecting those metrics that most strongly correlate with the site’s state of degradation measured by chemical or hydromorphological parameters;
- aggregating these core metrics into a multimetric index;
 - the scores or results of the metrics are combined in a simple multimetric index (usually the average of all scores);
- calibrating the stream-type specific assessment systems with independent data;
- defining quality classes of “high”, “good”, “moderate”, “poor” and “bad” ecological status for the selected stream types.

The consortium all together tested, independently for each of the 29 stream types, the correlation of a large number of metrics against the extent of degradation of a site as determined by assessment of the site protocol data (Ofenböck et al., 2004). Metrics that clearly respond to specific pollutants or stressors were considered most useful as a diagnostic tool (Karr & Chu, 1999). Furthermore, several criteria were followed:

- the metrics used should in combination cover diverse aspects of structure, composition, quality and function of the aquatic ecosystem;
- the metrics should deliver information on different components of the community;
- the metrics should be consistent with the country’s traditions in stream monitoring.

The selection process resulted in up to 18 suitable core metrics for the individual AQEM stream types (Hering et al., 2004). Most interesting in the multimetric indices development within AQEM is the final use of the criteria. In all cases it was clear that those metrics selected to construct a multimetric index showed a significant correlation with the respective stressor gradient.

Further developments in STAR

The STAR project (Standardisation of river classifications: Framework method for calibrating different biological survey results against ecological quality classifications to be developed for the Water Framework Directive. Contract no.: EVK1-CT-1999-00027, www.eu-star.at) was carried out between 2003 and 2005. The STAR project used the AQEM multimetrics development. AQEM was restricted to macroinvertebrates, STAR included several new countries than AQEM (Denmark, France, Great-Britain, Latvia, Poland, Slovakia) as well as three additional organism groups (macrophytes, diatoms, fishes). The metric types used belong to the categories: composition/abundance metrics, richness/diversity measures, sensitivity/tolerance metrics and functional metrics (Hering et al., 2006). A general procedure to select the most suited metrics is fully described by Hering et al. (2006). Metrics are calculated using existing autecology data on species. Environmental gradients are extracted through ordination analyses procedures on selected parameters. Correlation is used to select metrics whereby a number of criteria (e.g., being robust, reflecting quantitatively an impact gradient, founded on ecological principles, representing different components of the ecosystem) are added to select the final metrics. Those selected metrics are used to construct the multimetric. For diatoms no

multimetrics were developed. For fish the FAME approach has been adopted (www.fame.boku.ac.at). The new countries up to this point did not develop national multimetrics.

Germany and Austria have applied the experiences from STAR and AQEM and developed and integrated multimetric indices into their national assessment systems to achieve the EU Water Framework Directive demands for an integrated biological assessment for macroinvertebrates (Hering et al., 2004; Ofenböck et al., 2004).

In both countries modular and stream type-specific systems were generated, which are capable to distinguish the impact of different stressors. Due to the modular structure, the assessment systems integrate the impact of different stressors on the benthic invertebrates community and consist of three basic modules, developed to consider the main stressor types. The three modules are

- “organic pollution”
- “acidification”
- “general degradation”

For the module “Organic Pollution” the traditional Saprobic Index was adapted to a five class system and evaluated in relation to a stream type-specific reference value in both countries (the revised German Saprobic Index (DIN 38 410) (Rolauß et al., 2003); Austrian “Guidelines Saprobiology” ÖNORM M 6232, 1997; Moog et al., 1999; Stubauer & Moog, 2002). For acidification an acidification index (Braukmann & Biss, 2004) is designated for bioregions at risk of acidification, while multimetric indices are used for the evaluation of “general degradation”. Metrics for the indices were selected to address all major aspects (metric groups) of the biota, which are required in the WFD. In the Austrian classification scheme for the stressors “general degradation” furthermore distinguishes between two different indices for every stream type to address two diametrically opposed effects of stressors on running waters:

- “potamalisation” (e.g., caused by impoundment or siltation) and
- “rhythralisation/loss of diversity” (e.g., caused by river straightening (loss of habitats) or toxic contamination).

Metrics used for the multimetric indices are standardised in relation to metric values under

stream type-specific reference conditions. Indices are calculated by averaging the standardised metrics. The class boundaries finally were defined to result in classes of equal width. The final Ecological Quality Class in both countries is determined by the worst case applying all relevant modules.

Discussion and conclusions

Databases

There is a common agreement that the performance of any biological assessment approach increases with the quality rating of its ecological background. Consequentially there was a remarkable increase of taxalists that related ecological information to indicator taxa in the last 10–15 years. These taxalists include functional ecosystem characteristics, species traits and others more in ecological assessment. Although the newly developed methodologies are quite promising we are still away from having assessment tools that can be applied robustly and area-wide. The results of the STAR project contributed valuably to ecological status assessment of rivers but also clearly indicated gaps in the knowledge on aquatic ecology that need to be closed. A strong cooperation of basic limnology with applied aquatic ecologists who translate the scientific knowledge into easy understandable and applicable tools is still needed for achieving the target goal of a good ecological status of rivers and streams.

Multimetric indices and community approaches

Metrics that relate to specific stressors or characteristics of the ecosystem functioning provide, individually, a strong diagnostic tool. The effects of various stressors on the behaviour of specific metrics strongly depend on the knowledge of the distribution and ecological requirements of the respective species. Hering et al. (2006) clearly postulate that a harmonisation in developing a multimetric assessment system in Europe is an inevitable must. The authors suggest a normative methodology for the development and application of multimetric indices which is composed of the following steps: (1) Selection of the most suitable form of a multimetric index; (2) metric selection,

broken down into metric calculation, exclusion of numerically unsuitable metrics, definition of a stressor gradient, correlation of stressor gradients and metrics, selection of candidate metrics, selection of core metrics, distribution of metrics within the metric types, definition of upper and lower anchors and scaling; (3) generation of a Multimetric Index (general or stressor-specific approach); (4) Setting class boundaries; (5) interpretation of results.

On the other hand community approaches provide an integrated approach of the ecosystem but do not specifically point to a stressor or specific environmental condition.

In conclusion, using both a community approach together with a number of diagnostic metrics would provide a very strong tool for WFD proof water management.

Multiple stress and metric selection

In all cases it was clear that those metrics selected to construct a multimetric index showed a significant correlation with the respective stressor gradient. But selecting those metrics with a high correlation implies not including those metrics that provide information on weak stressors or healthy ecosystem components. For example, when a river is organically polluted a high correlation can be found between the organic load stressor with a saprobity metric. But at the same gradient a hydromorphological change can occur, and this is very often the case. Either metric selection is done along mono-stressor

gradients which is not explicitly explained in most of the literature or the effects of those less dominant stressors are ignored following the selection procedure as described in the AQEM manual (AQEM consortium, 2002). This mono-stressor based selection procedure does not correspond to one of the most important criteria a multimetric is based on, namely telling the user about a number of features of the respective ecosystem. In such case, the multimetrics construction procedure should much more accurately test each metric within each of the groups of metric within each individual the ecosystem feature.

Organism groups

All multimetric approaches developed in the AQEM and STAR projects only used macroinvertebrates although hydromorphology indices were developed and diatom, fish (FAME) and macrophytes indices were used. For these organism groups there were no multimetric indices developed due to lack of sufficient data, non-coherence with the WFD stream typology, detection of a scale of response problem and elaboration time. In future these problems should be overcome. Furthermore, an authentic multimetrics approach should include metrics of different organism groups.

Ecosystem components

The theory states that metrics should cover all ecosystem components. Looking at these

Table 1. The overall list of AQEM metric categories (Hering et al., 2004)

Metric category	Examples
Richness measures	Total number of taxa, number of EPT taxa
Composition measures	% Dominant taxon, % Oligochaeta
Diversity measures	Shannon–Wiener diversity index
Similarity/loss measures	Species deficit, missing taxa
Tolerance/intolerance measures	Saprobic index, BMWP, ASPT
Functional and trophic measures (Feeding measures)	% Filterers, index of trophic completeness, RETI
Habitat/mode of existence measures	% of clinger, number of (semi)sessil taxa
Current preference measures	% Limnophil, % rheophil
Zonation measures	Zonation Index, % littoral
Generation turnover measures	% Bivoltin, % univoltin
Individual condition measures	Contaminant levels, % diseased individuals

Table 2. Number of metrics per ecosystem feature per stream according to the AQEM results (Hering et al., 2004)

Stream type	Richness measures	Composition measures	Diversity measures	Similarity/loss measures	Similarity/intolerance measures	Tolerance/intolerance measures	Functional trophic measures (Feeding measures)	Habitat/mode of existence measures	Current preference measures	Zonation measures	Generation turnover measures	Individual condition measures	Total number of metrics	Number of metric categories
A01	2	3	1	1	2	1	1	1	1	1	1	10	10	6
A02	3	2	1	1	2	1	1	1	1	1	1	8	8	4
A03	2	3	1	1	2	1	1	1	1	1	1	10	10	6
A04	2	3	1	1	1	1	1	1	1	1	1	9	9	6
C01					2	1	1					3	3	2
C02	2				1	1						3	3	2
C03	1				1	1						2	2	2
D01		2			1	1	1	1	1	2		7	7	5
D02		1			1	1						2	2	2
D03		2			1	1			1	2		7	7	5
D04		1	1		2	1	2			2		8	8	5
D05	1	1	1		1	1	1	1				6	6	6
H01	1				1	1		2				4	4	3
H02	2		3		3	1	1	1	1	1		12	12	7
H03					1	2	1	1		1		5	5	4
I02	3	9			2	1	1					15	15	4
I03	2	6			1	1	1	2				12	12	5
I04	2	7	1		2	1						12	12	4
N01	1	4			1	1	1	1	1	1		10	10	7
N02	2	5			1	1	1			1		10	10	5
P01		1										1	1	1
P02		1										1	1	1
P03		1										1	1	1
S01	1				1		1					3	3	3
S02	1				1	1						3	3	3
S03	1				1							2	2	2
S04	1				1							2	2	2
S05			1		2							3	3	2
Total	30	52	10	0	35	15	10	6	13	0	0	171	171	8

components preferably metrics should cover system conditions (e.g., temperature regime), hydrology (e.g., current velocity conditions), physical structures (e.g., bank profile), water chemistry (e.g., nutrients), energy sources (e.g., production), biotic interactions (e.g., competition). Although the metric categories used (see Tables 1 and 2) list a number of ecological attributes, most relate to a restricted number of ecosystem components. Table 2 clearly shows that richness, composition and tolerance/intolerance measures dominate most multimetrics developed. Within these metrics the focus mainly goes for organic load and current conditions. Other attributes have not been used in composing a multimetric index due to sampling fuzziness (e.g., abundance measures) or lack of species based ecological knowledge (functional measures). A further development of more ecosystem and organism functioning related attributes and metrics is needed to fulfil the multimetric promise.

In the process of metric selection the criterion of correlation is discussable. If certain ecosystem components still are functioning in a more optimal way it does not mean that the related metric should be excluded from the assessment or multimetric. Because such metric also tells about the ecosystem condition. On the other hand one has to avoid an overemphasis of a single metric's type. Based on the STAR experience it is advised to embrace also a selection procedure that does include non-responding but informative metrics.

The STAR project paid attention to the need of the Water Framework Directive for monitoring the ecological status of rivers and streams in Europe. Based on the finding of the AQEM project a remarkable increase in the knowledge on bio-monitoring methodologies is achieved. With respect to multimetric approaches the output of AQEM and STAR has been successfully incorporated in the development of national bio-monitoring networks. But, as usual in scientific activities, each fissure that could be closed opened much more gaps that need to be filled. We therefore strongly encourage the European administration to "make hay while the sun shines" by utilising the scientific manpower of the AQEM and STAR consortium in follow-up research programme on many of the practical issues associated

with the implementation of the Water Framework Directive.

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